M.Sc. Thesis

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Environomical Pathways for Sustainable Energy Systems

Numerical Simulation and Feasibility Study of a Hybrid CSP-Biomass Power Plant

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Abstract

World's demand for energy, and in particular for electricity, is growing rapidly. In this context, and with an increasing pressure in meeting international goals for climate mitigation, Concentrating Solar Power (CSP) seems one of the most promising technologies presenting the great advantage, when compared with other RES, of providing firm and dispatchable electricity, especially when deployed with thermal energy storage (TES) systems. Even if capable of providing both firm and flexible generation, representing a great alternative to both renewable hydropower plants and conventional fossil fuel-based power plants, its economics, highly dependent on the costs of the capital, still keeps the value of the LCOE very high. Moreover, the minimum requirements for the solar resource, an average DNI range of 1800–2000 kWh/m^2 year, limit the implementation of this technology. As an alternative to CSP with TES systems, CSP power plants hybridized with biomass combustion technology show the advantages of improved performance, with higher efficiency and number of equivalent operating hours, and better economics, with lower capital costs and LCOE.

The numerical simulation of the only existing CSP-biomass power plant, the 25 MW *Termosolar Borges* located in Lleida, Spain, performed through the creation of a model, and proper validation of the same comparing the results obtained with the reference data, allows the collection of important technical and economic information regarding the operation of the hybrid plant. The same model is used to do the upscaling of the reference plant, and simulate the 50 MW hybrid power plant. The results obtained show that the 25 MW hybrid plant, characterized by an average DNI of 1780 kWh/m^2 year, is capable of generating 98800 MWh/year of electricity, being competitive with conventional 50 MW CSP plants without TES, characterized by average DNI of 2000 kWh/m^2 year and higher, and expected outputs in the range of 100000-110000 MWh/year. With an investment of 153 million €, the LCOE obtained is 150.9 €/MWh$_e$, lower than the LCOE of conventional 50 MW CSP plant without TES, in the range of 175-250 €/MWh$_e$. The performance of the upscaled 50 MW hybrid power plant is even better, capable of generating 197118 MWh/year of electricity, overcoming the electricity generation of conventional 50 MW CSP plants with TES characterized by expected outputs in the range of 160000-180000 MWh/year. With an investment of 274 million € and an LCOE of 136.6 €/MWh$_e$, competitive with the investment and LCOE of CSP plants with TES, respectively in the range of 310-410 million € and 116-200 €/MWh$_e$, the 50 MW hybrid power plant shows to be a very attracting investment.

The feasibility study highlights how the economics of hybrid power plants is highly dependent on the price of the biomass feedstock: an increase in its cost leads to a higher LCOE, due to the increased O&M costs. However, with growing biomass prices, it becomes more convenient to build hybrid power plants, including the hybrid CSP-biomass plants analyzed in this work. In fact, the hybridization of CSP mitigates the effect of the increased prices for the renewable fuel. The DNI also affects the overall performance of hybrid power plants. An average DNI range of 1600–1800 kWh/m^2 year has proved to be sufficient to assure technical and economic feasibility, extending the potential of hybrid technology to European countries characterized by lower levels of DNI. Also at World level, the implementation of the hybrid technology in countries with higher DNI is even more advantageous, reducing the biomass requirements and lowering the LCOEs. In conclusion, even if CSP is now limited to the areas around the "sun belt", the results obtained highlight that the hybrid CSP-biomass technology could make it evolve into an affordable and scalable alternative to conventional power generation at competitive levels, representing the only alternative to actual complex and expensive TES systems.

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Glossary

	Abbreviations
CSP	Concentrating Solar Power
DNI	Direct Normal Irradiation
GHI	Global Horizontal Irradiation
PV	Photovoltaics
RE	Renewable Energy
RES	Renewable Energy Sources
HTF	Heat Transfer Fluid
TES	Thermal Energy Storage
ST	Solar Tower
DSG	Direct Steam Generation
PT	Parabolic Trough
LF	Linear Fresnel
PD	Parabolic Dish
O&M	Operation & Maintenance
FiT	Feed-in Tariff
IGCC	Integrated Gasification Combined Cycle
CHP	Combined Heat and Power
BFB	Bubbling Fluidised Bed
CFB	Circulating Fluidised Bed
GHG	Greenhouse Gases
NG	Natural Gas
BU	Biomass Unit
PB	Power Block
TLP	Turbine Load Point
HP	High Pressure
LP	Low Pressure
TDR	Turn-down Ratio

TMY	Typical Meteorological Year
LHV	Lower Heating Value
EPC	Engineer-Procure-Construct
HRSG	Heat Recovery Steam Generator
BOP	Balance of Plant
LCOE	Levelised Cost of Electricity
CAPEX	Capital Expenditure
OPEX	Operational Expenditure
R&D	Research & Development
MENA	Middle East and North Africa
SMEs	Small and Medium-sized Enterprises

	Latin Symbols
C_p	Specific heat capacity [W/m^{2}K]
T	Temperature [K]
d	Discount rate
A_{eff}	Effective area [m^2]
A	Area [m^2]
UA	Overall heat transfer coefficient [W/K]
K	Incident angle modifier
M	End losses factor
Sh	Collector shading factor
WS	Wind speed [m/s]
h	Enthalpy [J/kgK]

	Greek Symbols
α	Annualisation factor
β	Discount factor
η	Efficiency

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1. Introduction and Literature Review

1.1. Motivation and Scope of the Present Work

The world's demand for energy grew by 2.1% in 2017, more than twice the previous year's rate, and electricity demand by 3.1%, according to new data from the International Energy Agency (IEA). In this context, and with an increasing pressure in meeting international goals for climate mitigation, RE systems able to generate a large amount of clean electricity are gaining always more attention. Concentrating Solar Power (CSP) seems one of the most promising technologies presenting the great advantage, when compared with other RES, of providing firm and dispatchable electricity, especially when deployed with thermal energy storage (TES) systems. This capability of generating electricity whenever needed by an electric utility to meet consumer demand, providing both firm and flexible generation, makes CSP a valid alternative to both renewable hydropower plants and conventional fossil fuel-based power plants. However, its economics, highly dependent on the costs of the capital, still keeps the value of the LCOE very high. Moreover, the minimum requirements for the solar resource limit the implementation of this technology. In fact, most of the European CSP power plants in operation are located within the average Direct Normal Irradiation (DNI) range of 1800–2000 kWh/m^2 year, necessary for guaranteeing the technical and economic feasibility of those projects. Nonetheless, a DNI below that range may be useful for hybrid technologies. CSP has shown its ability to integrate with fossil fuel-based generation sources in "hybrid" configurations, and Integrated Solar Combined Cycles (ISCC) power plants are just one example. But also completely renewable hybrid systems are possible if hybridization is realized integrating CSP with the well-known biomass combustion technology. The integration of the biomass boiler into the CSP power plant, thanks to their complementarity as primary energy resources, lead to the advantages of improving the flexibility and competitiveness of the power plant, increasing its electrical efficiency and number of equivalent operating hours, finally improving the overall performance of the power plant and reducing its capital costs and LCOE. So, even if CSP is now limited to the areas around the "sun belt", the hybrid concept could make it evolve into an affordable and scalable alternative to conventional power generation at competitive levels, representing the only alternative to actual complex and expensive TES systems. Due to the low level of R&D, many Spanish and International companies could take advantage, investing in R&D in the early stage of deployment of this attracting technology, counting on their expertise and know-how in the CSP field. The large-scale deployment of such innovative hybrid technology could induce various benefits also at a National level, such as energy security, climate protection, income from exports of electricity as well as components and services, private sector development and job creation. The main purpose of this work is to analyze the characteristics, strengths and limits of the hybrid CSP-biomass technology, starting from the numerical simulation of the only existing hybrid power plant: the *Termosolar Borges* located in Lleida, Spain. The potential of the hybrid technology is also assessed, performing a feasibility study and analyzing the technical and economic performance of an upscaled hybrid power plant under different operating conditions. In *Chapter 1*, an extensive literature review is performed, in order to introduce the basic principles, advantages and limits of the CSP and Biomass technologies, as well as the hybrid technology. *Chapter 2* is dedicated to the numerical simulation of the *Termosolar Borges* power plant, to analyze how a hybrid power plant operates and to get important technical and economic information. These results, properly validated by comparing them to the real data taken from the *Termsolar Borges*, are used in *Chapter 3* to do the upscaling of the reference plant to the size of conventional CSP power plants with TES systems, 50 MW of gross installed capacity. The upscaled plant is then simulated and analyzed as in the case of the reference plant. The performance of the reference and upscaled 50 MW hybrid power plants are then compared to conventional CSP power plants, with and without TES, from both a technical and economic point of view. In *Chapter 4*, a feasibility study is conducted in order to assess how the performance of the hybrid power plant change depending on different technical, economic and geographic conditions, and evaluate its potential implementation in different worldwide locations. Finally, in *Chapter 5*, some considerations regarding the business potential of the hybrid technology are made, as well as regarding the social and economic impacts that the deployment of such innovative hybrid technology could have.

1.2. Concentrating Solar Power (CSP) Technology

1.2.1. Basic Principles

Concentrating Solar Power (CSP) plants use mirrors to concentrate sunlight onto a receiver, which collects and transfers the solar energy to a heat transfer fluid that can be used to supply heat for end-use applications or to generate electricity through conventional steam turbines [1]. CSP plants can be equipped with a thermal energy storage system, which increases the capacity factor and dispatchability of the plant, to allow for heat supply or electricity generation also during sunless hours, when the sky is cloudy, and at night. Unlike solar photovoltaics (PV), CSP uses only the direct component (DNI) of sunlight and provides heat and power only in regions with high DNI (i.e. Sun Belt regions like North Africa, the Middle East, the southwestern United States and southern Europe) [1].
CSP power plants consist of three major subsystems [2]:

- The solar field, which concentrates the solar energy onto the receiver, where it is collected by the Heat Transfer Fluid (HTF). There are three types of HTF: water, oil or molten salts. In the last two cases, additional heat exchangers are required for running the steam cycle.

- The power block, where the produced steam is used to spin a turbine and produce electricity. Usually, steam Rankine cycles are employed.

- Additionally, a thermal energy storage (TES) system can be installed, in order to store excess energy collected during periods of high irradiation and utilize it during sunless hours, or at night. It can provide dispatchable energy also when the solar resource is scarce.

In order to increase even more the power plant availability, it can be hybridized with fossil fuels, usually natural gas or coal, or renewable energy sources, such as biomass. Since this aspect is central to the thesis, it will be further discussed in the following chapters. Depending on the process through which the solar energy is collected and transferred to the HTF, CSP systems are classified into four different technologies.

1.2.2. Solar Tower (ST)

CSP tower systems, often referred to as power towers or central receivers, use a field of mirrors called heliostats that individually track the sun on two axes and redirect sunlight to a receiver at the top of a tower [2]. The concentrating ratios that can be achieved through this technology are around 600-1000, with the possibility of achieving working fluid temperatures of around 500-800 °C. Consequently, higher thermal efficiencies are achieved with this type of technology. Different heat transfer fluids can be used, including steam, air and molten salts. The last one is preferred for tower systems since it can be easily coupled to a thermal energy storage (TES) system, thus allowing higher capacity factors, around 60%

[3], and increased dispatchability of the plant. Direct steam generation (DSG) in the receiver eliminates the need for a heat exchanger between the primary heat transfer fluid and the steam cycle, but makes thermal storage more difficult [1]. It is the most mature technology today, together with parabolic trough technology. One good example of such plants is the Gemasolar power plant, located in Sevilla, Spain. With 20 MW of installed capacity and 15 hours of storage, the plant can operate at nominal condition up to 5000 hours per year [3]. It is situated close to the PS10 solar power plant, the world's first commercial concentrating solar power tower plant, with 11 MW of installed capacity and 1 hour of storage [4].

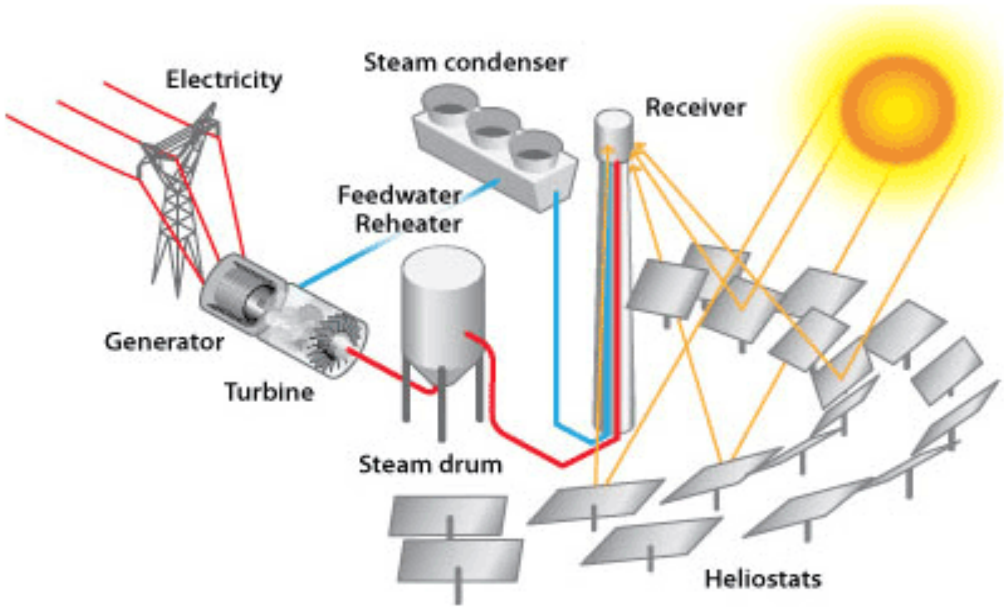

Figure 1.1: CSP Central Tower power plant [5]

1.2.3. Parabolic Trough (PT)

CSP trough, also referred to as parabolic trough, systems use curved mirrors and single-axis tracking to follow the sun throughout the day, concentrating sunlight on thermally efficient receiver tubes or heat collection elements [2]. The concentrating ratios that can be achieved through this technology are around 70-100, with working fluid temperatures of up to 400 °C. Usually, steam and thermal oil are used as heat transfer fluids, but the potential of molten salts at 550°C for either heat transfer or storage purposes is under demonstration [1]. The fluid circulates in the tubes absorbing the sun's heat before passing through multiple heat exchangers to produce steam. Then the steam is used to spin a turbine to generate electricity. Utility-scale collector fields are made up of many parallel rows of troughs connected by receiver tubes in series. Rows are typically aligned on a north-south formation axis to track the sun from east to west for an increased efficiency [2]. A very important aspect of PT technology is that it is the most suitable for hybridization with fossil fuels (e.g. natural gas or coal) or renewable energy sources (e.g. biomass), for increasing the dispatchability and availability of the solar power plant. The PT technology is the most mature and commercially proven of the CSP technologies. An example of such plants is the Andasol (AS), located in Granada, Spain. With an installed capacity of 150 MW, divided into three plants of 50 MW each, and 7.5 hours of storage, the plant can operate at nominal condition up to 3500 hours per year with a capacity factor of 41% [6].

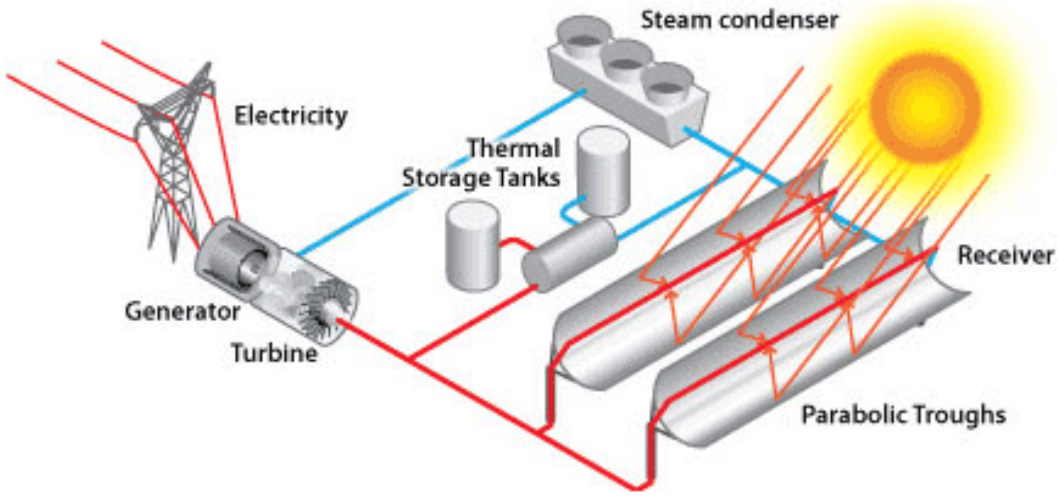

Figure 1.2: CSP Parabolic Trough power plant [5]

1.2.4. Linear Fresnel (LF)

Linear Fresnel reflector, also referred to as compact or concentrating linear Fresnel reflector, systems are made up of flat or nearly flat mirror arrays that reflect solar radiation onto elevated linear absorbers or receiver tubes [2]. The basic principle is similar to the one of PT, but the main difference is in the reflector which is made up of mirror arrays at different angles, equipped with a single-axis tracking system, to concentrate the sunlight onto a fixed receiver [1]. The concentrating ratios achieved are very low, around 10-40, and so are the working fluid temperatures of up to 300 °C. This converts into the lowest capacity factor, around 10%, among all the different CSP technologies. The typical heat transfer fluid is water, which circulates through the tubes and is converted into steam. Steam can also be generated directly in the solar field (DSG), eliminating the necessity for costly heat exchangers. LF is the most recent CSP technology with only a few plants in operation (e.g. 1.4 MW in Spain, 5 MW in Australia and a new 30-MW power plant, the Puerto Errado 2, in Spain, which started operation in September 2012) [1] [7].

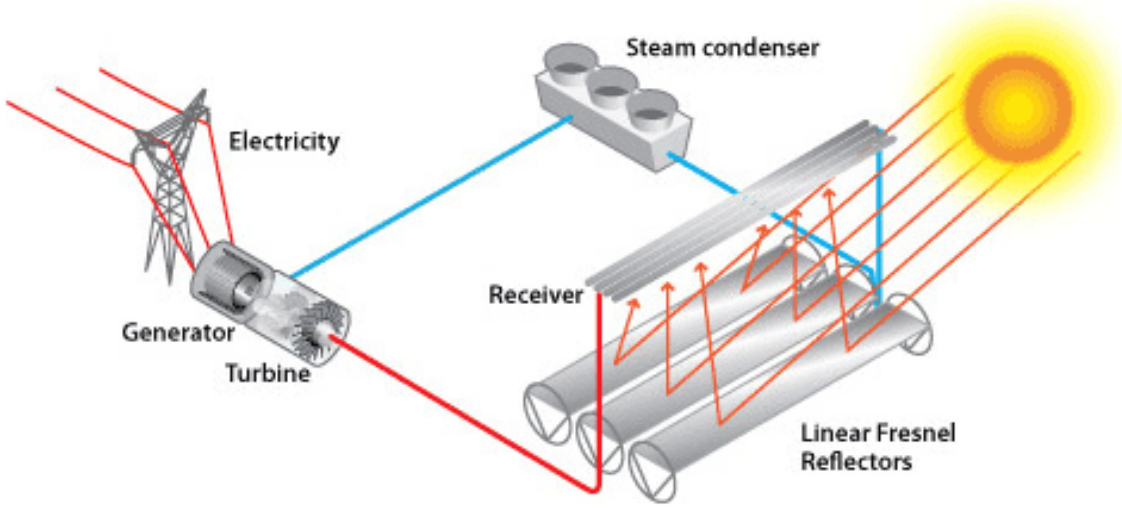

Figure 1.3: CSP Linear Fresnel power plant [5]

1.2.5. Parabolic Dish (PD)

Parabolic dish, or dish engine, systems are individual units comprised of a solar concentrator, a receiver, and an engine or generator. The concentrator typically consists of multiple mirror facets that form a parabolic dish, which tracks the sun on two axes and redirects solar radiation to a receiver [2]. The receiver, located at the focal point of the reflector, contains a motor-generator that can operate using a Stirling engine or a small gas turbine. These systems are very compact, with typical sizes between 10-25 kW, and can reach concentrating ratios of up to 3000, with temperatures up to 1000 °C. Due to high tracking efficiency, high operating temperatures and high-efficiency conversion cycles, the Parabolic Dish is the most efficient CSP technology. Moreover, the collectors are highly modular and very suitable for distributed generation. However, they have yet to be deployed on any significant commercial scale [1], and the direct conversion of heat into electricity limits the possibility of hybridization or integration of a thermal energy storage (TES) system.

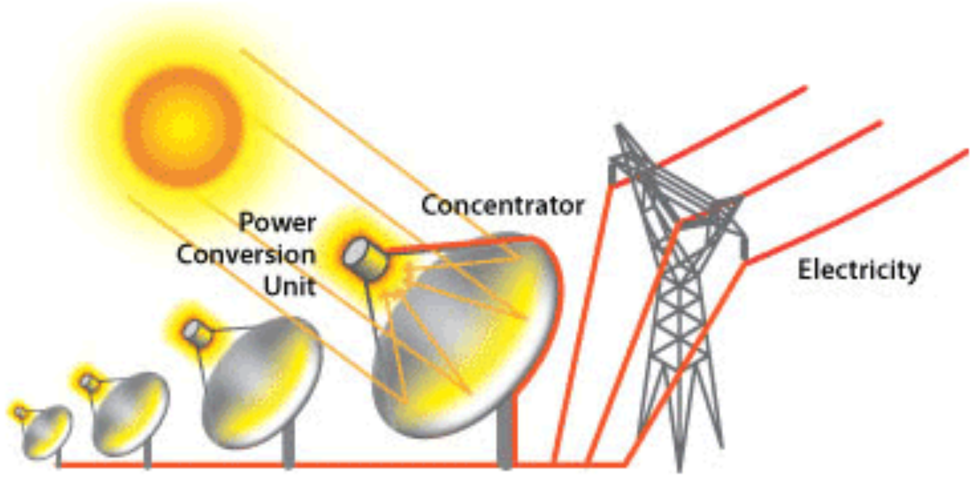

Figure 1.4: CSP Parabolic Dish power plant [5]

1.2.6. Advantages and Disadvantages of CSP

CSP technology can be considered a RES. It exploits the energy that comes from the sun, being a renewable, non-polluting and efficient source of electricity. GHG emissions for CSP plants are estimated to be in the range of 15-20 gCO_2-eq/kWh, much lower than emissions from fossil fuel-based power plants, around 400-1000 gCO_2-eq/kWh, respectively for natural gas and coal [8]. Moreover, it does not produce any of the harmful emissions and wastes associated with conventional fossil fuel-based power plants (e.g. sulfur dioxide, nitrogen oxide, lead), it avoids the environmental risks associated with nuclear power plants (e.g. long-lasting waste) [9]. However, it presents some limits mainly related to land and water use. Land use is not a big problem since most of the time CSP plants are located in areas with limited amenity or aesthetic value (e.g. desert regions) [8]. Water is consumed by the cooling system of the power block, and consumption could be reduced by cooling with air instead, even if this lowers the efficiency of the system.

Compared with other RES, CSP presents the great advantage of being able to produce electricity on demand, providing a reliable and dispatchable source of renewable energy, especially when deployed with thermal energy storage. Therefore, it can provide electricity whenever needed by an electric utility to meet consumer demand, also performing like a traditional base-load power plant [10]. This aspect, together with the capability of providing both firm and flexible generation, makes CSP a valid alternative to both renewable hydropower plants and conventional fossil fuel-based power plants. In the context of an increased penetration of renewable energy in the generating mix of a country, CSP can substitute both coal-fired power plants, for base-load generation, and gas-fired power plant, providing the variable reserve to meet peak demand if enough energy is stored in the storage system. Another distinction of CSP is its ability to integrate with fossil fuel-based generation sources in "hybrid" configurations [10]. Combining traditional fossil fuel-based power plants with emissions-free CSP, it is possible to create a hybrid system to enhance the performance of both systems, at the same time reducing the environmental impact of the new plant. Also completely renewable hybrid systems are possible, without penalizing the performance of the power plants, if hybridization is realized integrating CSP into existing biomass-fired power plants, as it will be further discussed in the following chapters.

The main barrier to the deployment on large scale of CSP technology is that its economics is highly dependent on the costs of the capital. The investment and financing costs account for more than 80% of the electricity cost, the rest being fixed and variable O&M costs. Current investment costs can range from 4600 $/kW, for a PT system with no thermal energy storage, to 10500 $/kW, for a ST plant with 15 hours of storage [1]. Compared to conventional power plants, the typical cost of a NGCC (Natural Gas Combined Cycle) is in the order of 1000 $/kW, while supercritical coal plants cost around 3000 $/kW. Nuclear power plants are more capital intensive, costing around 5500-6000 $/kW [11]. According to recent projections, the cost will be competitive with natural gas by 2020 and with coal by 2025, due to both economy of scale and improved manufacturing. It is already a cleaner and more cost-effective solution than oil. Overall, the CSP technology represents a solution with same technical quality but enhanced economic stability compared to conventional fossil fuel-fired power plants [11].

Compared to other RES, CSP is less mature with only 4.8 GW of installed capacity, while PV and Wind account respectively for 303 GW and 587 GW [12]. However, if we internalize all the external costs, such as carbon emission, pollution, storage needed, transmission upgrade, price volatility, decommissioning and insurance cost, as we can see in Figure 1.5 CSP technology is one of the best choices among the main RES.

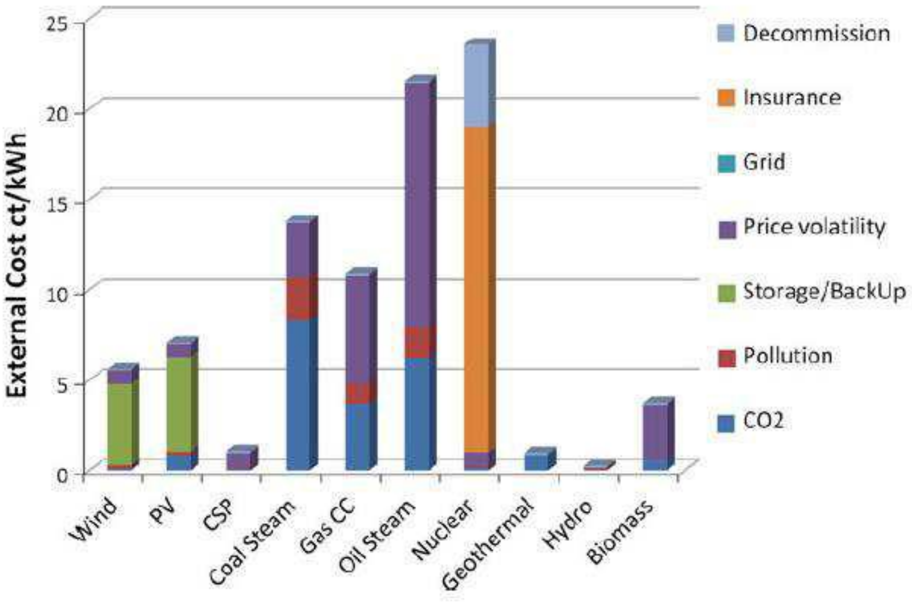

Figure 1.5: Comparison of the external costs for different energy sources [13]

1.2.7. Worldwide CSP Market

The first CSP power plants, named Solar Energy Generating Systems (SEGS), were built in the 1980s in California. With a cumulative total capacity of 354 MW, they are the second largest solar thermal generating facility after the Ivanpah Solar Power Facility, which entered in operation in 2013 with a gross capacity of 392 MW, also in California. Today some emerging markets are driving the development of CSP technology worldwide, namely China, India, Northern and Southern Africa, Middle East.

China concentrated solar power market is predicted to exceed 7 GW by 2025. The growth over this timeframe is expected to be of over 20%. India concentrated solar power market size for 2015 was valued over USD 1 billion. Favorable government initiatives towards sustainable energy with rising electricity demand will favor the industry growth. Morocco has introduced a USD 9 billion national solar power plan to install 2GW of solar power capacity across Morocco by 2020 [14], and in 2016 brought the 160 MW Noor I plant online, part of the 500 MW CSP complex in Ouarzazate expected to be fully operational by the end of this year [15]. Dubai launched last year the world's largest CSP project, at Mohammed bin

Rashid Al Maktoum Solar Park, to generate 700MW of clean energy. Even if the number of countries with installed CSP is growing, Spain and the United States remain the global leaders, with an installed CSP capacity of respectively 2304 MW and 1745 MW (see Figure 1.6).

In 2002, Spain was the first European country to introduce a "feed-in tariff" funding system for solar thermal power, which determined the development of CSP in the country. In 2012, the feed-in tariff (FiT) program implemented in 2007 was canceled by the Government for new applicants, so that it would not be awarded to CSP plants beyond the 2304 MW approved in 2009 to enter into operation before 2014 [16]. In the last years, we assisted to a reduction of the overall costs of CSP technology, due to the experience gained by the countries involved in the operation of CSP power plants and research projects. Further costs reduction will be determined by market opportunities and implementation of new technologies.

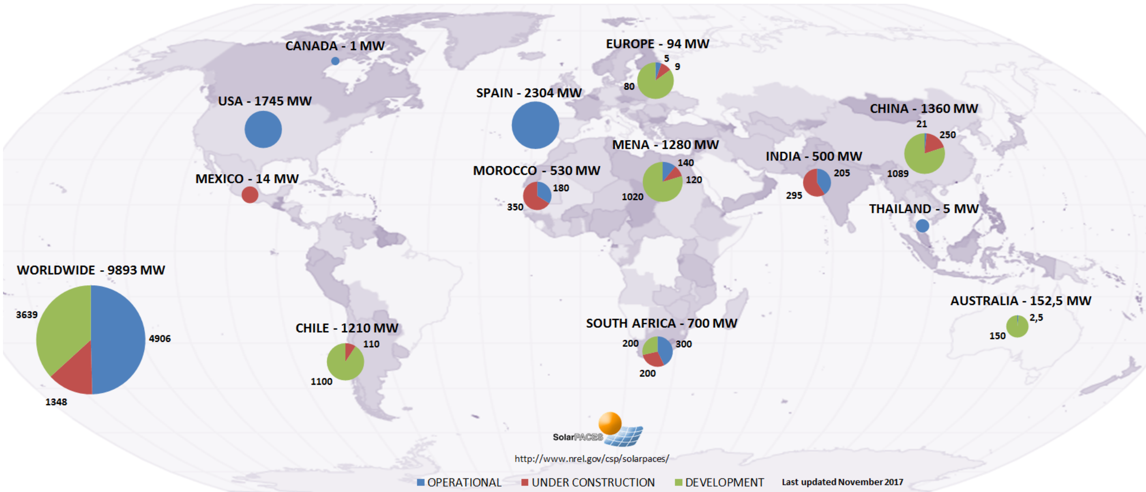

Figure 1.6: CSP projects around the world divided by operational, under construction and in development [17]

1.3. Biomass Power Generation (Biopower) Technology

1.3.1. Basic Principles

Biomass is any organic matter that can be used as an energy source, either directly or in the form of a biofuel. Plants are able to convert solar energy into chemical energy, storing it in the form of carbohydrates, which is then exploited to generate heat and power through different processes depending on the type of biomass [18]. There are four main sources of biomass energy [19]:

- Wood and agricultural products: the largest source of biomass energy today, including forest residues (e.g. dead trees, branches), wood chips and agricultural waste products (e.g. fruit pits, corncobs). A large variety of tree species and types of plants can also be specifically grown, with the purpose of using it as fuel or feedstock for industrial processes. These types of biomass can be directly burnt for producing electricity and heat, using burners or boilers in conventional power plants.

- Municipal Solid Waste: commonly known as trash or garbage, it is composed of organic and inorganic material, which can be burnt to produce energy since it has still some heat energy. Not all garbage is biomass; half of its energy content comes from plastics, which are petroleum-based, and constitute quite a large part of it. Power plants that burn garbage for energy are called waste-to-energy plants and are based on the same operating principle as conventional coal-fired power plants.

- Landfill gas and Biogas: it is methane gas produced by buried waste in deposit sites for waste material, known as landfills. Methane gas is collected by a piping system, purified and used as a fuel. Biogas can also be produced using energy from agricultural and human wastes, through biogas digesters, which are airtight containers or pits lined with steel or bricks. Waste put into the containers is fermented without oxygen to produce a methane-rich gas. This gas can be used to produce electricity, or for cooking and lighting.

- Alcohol fuels: mainly ethanol and biodiesel; the first one made by fermenting the sugars and starches found in plants and then distilling them, the other made by chemically reacting alcohol with vegetable oils, animal fats, or greases, such as recycled restaurant grease. Any organic material containing cellulose, starch, or sugar can be made into ethanol, while most biodiesel today is made from soybean oil. Both are used mainly as transportation fuels, with the biodiesel mixed in various ratios with petroleum diesel.

Regarding power generation, several technologies and energy conversion chains can be utilized for exploiting biomass energy, which differ mainly for the biomass characteristics, the conversion principle and the obtainable products. The three major conversion chains are based on *Thermochemical*, *Biochemical* and *Mechanical* processes, which include a primary conversion technology that converts biomass into an intermediate product (e.g. hot water, steam, gaseous or liquid products), and a secondary conversion technology which transforms these products into heat and power [20]. The most adopted systems are:

- Direct combustion: it is a process in which the fuel is burnt with oxygen from air to release the stored chemical energy as heat in burners, boilers or internal combustion engines, at temperatures around 1200-1700 °C. The heat generated from combustion can also be used to produce steam, to be used in secondary conversion technologies, like steam turbines in an Organic Rankine Cycle (ORC), to generate electricity. The biomass utilized must be of low moisture content, since part of the heat is utilized to evaporate the water, reducing the efficiency.

- Gasification: it is a high-temperature thermochemical conversion process designed to convert solid biomass into a gaseous fuel, the syngas. It involves the partial oxidation of biomass in a fuel rich environment, at temperatures around 700 °C. After appropriate treatment, the produced gas can be burnt directly for cooking or heat supply, or used in secondary conversion technologies, such as gas turbines and engines to produce electricity or mechanical work [21]. Integrated Gasification Combined Cycle is one of the most attracting power generation processes to be coupled with gasification, both in terms of high efficiency and reduced environmental impact.

- Pyrolysis: it is a thermochemical process in which biomass is exposed to high temperatures in the absence of air, causing the biomass to decompose [22]. The end product is a mixture of solids (char), liquids (oxygenated oils), and gases (methane, CO, and CO_2). Depending on the duration and temperature of the process, it is possible to distinguish between slow pyrolysis, around 300°C for up to few days, and fast pyrolysis, in which organic materials are rapidly heated up to 500-600 °C. The goal of fast pyrolysis is to increase the yield of the liquid product, to produce a liquid fuel, called bio-oil or pyrolysis oil, which can be used for heating or power generation [21]. The main benefit of pyrolysis, relative to combustion and gasification, is that its liquid fuel product is easier to transport than either solid or gaseous fuels. (This means that the pyrolysis plant does not have to be near the end-user point of the bio-oil, but can instead be located near the biomass supply, resulting in lower fuel transportation costs.)

- Anaerobic digestion: it is a biochemical process in which organic matter is decomposed by bacteria in the absence of oxygen, to produce methane and other by-products. The resulting biogas is composed of 60-65% methane and 30-35% carbon dioxide, with the rest a mixture of other gases (mostly nitrogen). After appropriate treatment, biogas can be used directly for cooking and heating or used in secondary conversion technologies such as gas engines and turbines. High-moisture biomass feedstocks are especially well-suited for the anaerobic digestion process. The advantage of anaerobic digestion over thermochemical processes is that it produces a concentrated nitrogen fertilizer, and also neutralizes wastes that would otherwise be dumped into the environment [23].

Other conversion technologies can be implemented for exploiting biomass energy, with other primary applications different from power generation: these are *Dilute Acid Hydrolysis*, *Liquefaction* and *Transesterification*. While the first two technologies are used for producing various liquid fuels or chemicals, Transesterification is used for producing biodiesel, used primarily for transportation.

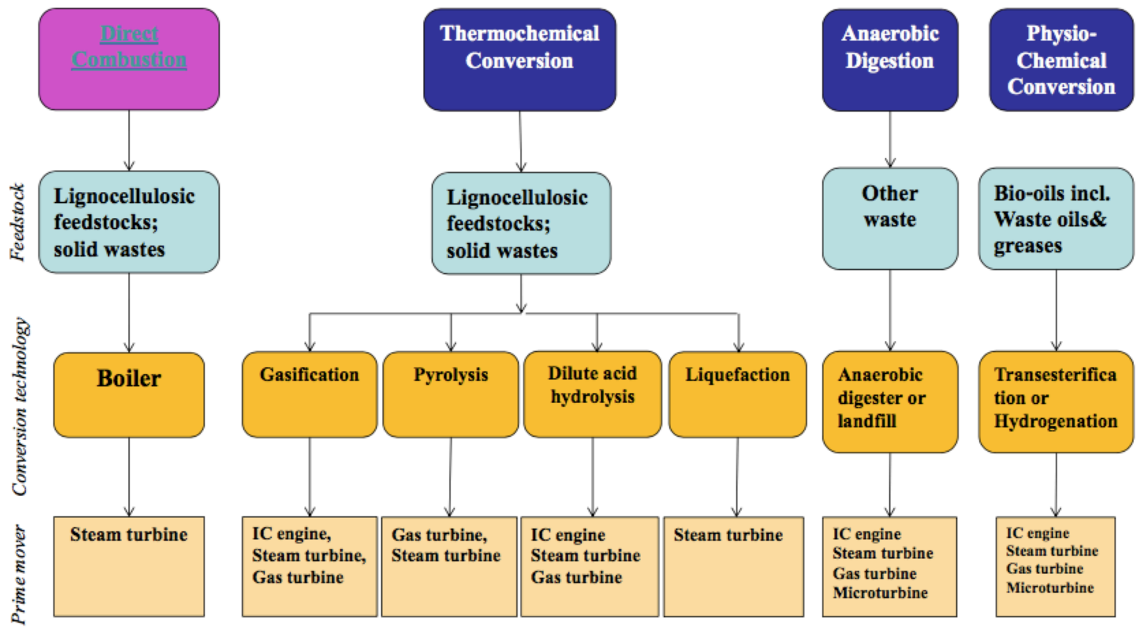

Figure 1.7: Technologies for Biomass Power Generation [20]

Among the different technologies, direct combustion facilities, which burn biomass directly to generate electricity, provide more than 90% of the energy generated from biomass worldwide. This is largely because direct combustion is a well-understood, well-developed and widely available technology that can be easily integrated with existing infrastructure [21]. Being the most proven technologies for heat and power generation, especially due to their potential of being integrated together with other power generating technologies (e.g. Co-firing, IGCC power plants), Combustion and Gasification technologies are further analyzed in the following chapters.

1.3.2. Combustion Technology

Combustion is a process in which the fuel is burnt with oxygen from air to release the stored chemical energy as heat in burners, boilers or internal combustion engines. Temperatures are in the range of 1200-1700 °C, with efficiencies around 70-85%, depending on the heating value and moisture content of the fuel, the excess air and type of combustor [24].

Combustion is the most common way of converting solid biomass fuels into energy. Worldwide, it already provides over 90% of the energy generated from biomass, mainly for cooking and space heating, and mostly in developing countries, where biomass combustion provides basic energy for rural households and for process heat in a variety of traditional industries [25]. As pointed out in [25], despite this so-called traditional biomass use, other applications can be highlighted. Industrial use of biomass, for both process heat and electricity production, takes place in a combustor or furnace. The heat can be used directly or for producing steam in a boiler, which can then expand through a steam turbine to generate power in an ORC cycle. Steam can also be extracted for use in industrial processes, or community district heating purpose, in Combined Heat and Power (CHP) applications. Due to the moisture content of the fuel and the size of conventional plants, usually lower than 50 MW, the net electrical efficiencies are around 25%, while in CHP plants they can be even lower but with much higher net overall efficiencies, around 70-80%. Only about 11% of the fuels are biomass resources, being the rest coal, natural gas, crude and refined oils (e.g. gasoline, diesel and kerosene). Regarding biomass power generation at an industrial level, the most common technologies are furnaces with boilers together with large-scale systems. In this second category, fixed bed (underfeed stoker & fixed or moving grate), fluidized bed (bubbling & circulating fluidized bed) and pulverized fuel combustors are included [20]. BFB combustors are of interest for plants with a nominal boiler capacity greater than 10 MW_{th}. CFB combustors are more suitable for plants larger than 30 MW_{th}. The minimum plant size below which CFB and BFB technologies are not economically competitive is considered to be around 5-10 MW_e [26].

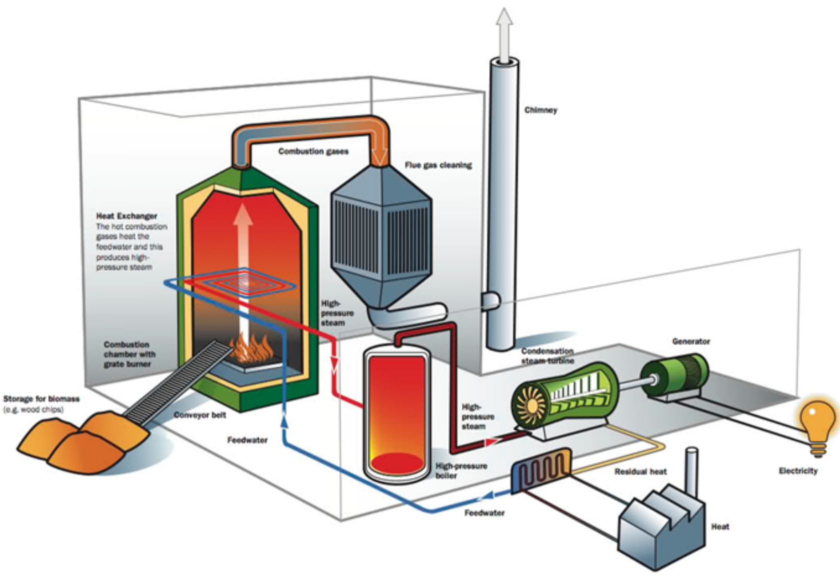

Figure 1.8: Combined Heat & Power biomass power plant [27]

Another interesting use of biomass for power generation is the so-called *Co-firing*. It consists in burning biomass together with coal in conventional coal-fired power plants. The fuel properties of biomass differ significantly from those of coal, some of which are ash contents, a generally high moisture content, potentially high chlorine content, relatively low heating value, and low bulk density. They also vary considerably between different types of biomass, ranging from woody to herbaceous. These properties affect design, operation, and performance of co-firing systems [28]. There are three types of biomass co-firing: *Direct co-firing*, with the biomass burnt directly in the existing coal furnace. Direct co-firing can be done either by pre-mixed the raw solid biomass (generally in granular, pelletised or dust form), with the coal in the coal handling system or by the milling it and directly injecting it into the pulverised coal firing system; *Indirect co-firing*, with the biomass first gasified before the resulting syngas is combusted in the coal furnace; *Parallel co-firing*, with the biomass burnt in a separate boilers, and utilisation of the steam produced togheter with the one coming from the main coal power station steam circuit [29]. This last parallel configuration is very similar to the principle of operation of hybrid CSP-biomass power plants, as it will be further analyzed in the following chapters.

1.3.3. Gasification Technology

Gasification is a thermochemical conversion process designed to convert solid biomass into a gaseous fuel, syngas - also known as producer gas. This is accomplished through a partial combustion, heating the biomass up to 700 °C, in an oxygen-deficient environment [30]. In fact, the amount of oxygen required for gasification must be controlled, with equivalency ratios (i.e. the ratio of the actual air-fuel ratio to the stoichiometric one) between 0.25 and 0.35. This represents the main difference with respect to combustion and pyrolysis processes, in which the equivalency ratios are 1 or higher (excess oxygen conditions) and zero (anaerobic conditions). Combustible components of the gas include carbon monoxide, hydrogen, methane and small amounts of ethane and propane. The exact composition of the syngas depends on the operating temperature and pressure as well as the composition of the biomass feedstock. In general, higher pressures tend to produce more methane and water vapor and improve the carbon conversion efficiency of the gasifier. Higher temperatures tend to produce more CO and hydrogen. After appropriate cleaning from pollutants and contaminants (i.e. gas cleanup), the produced gas can be burned directly to produce heat or used in secondary conversion technologies such as gas turbines and engines to produce electricity or mechanical work [30].

There is a huge variety of gasification technologies, which makes difficult to group and categorize them because of the huge variety of process variables. What must be pointed out is that gasification is an emerging alternative for power generation, which has the great advantage over combustion to expand the use of solid fuel, including practically all the uses of natural gas and petroleum. It allows the use of cleaner and more efficient power conversion processes to produce power, such as gas turbines and fuel cells, and/or chemical synthesis to produce ethanol and other value-added products. Regarding power generation at an industrial level, syngas can be fired in traditional boilers to generate steam and run a steam

cycle, with net electrical efficiencies close to direct combustion processes, around 25%. Higher efficiencies can be achieved through the Integrated Gasification Combined Cycle (IGCC) concept, in which the heat of exhaust gases coming from the gas turbine is recovered to produce steam in a boiler, which can then expand through a steam turbine to generate power. The overall efficiency can rise up to 45%. However, IGCC plants are based on the gasification of coal, not biomass feedstocks, to produce the syngas. It has still a great potential in relation to the upgrade of old coal-fired power plants, especially in order to reduce the total GHG emissions [30].
One interesting aspect of the syngas combustion using boiler technology is that, similarly to biomass combustion, also biomass gasification can allow the *Co-firing.* In fact, the syngas can be co-fired in existing fossil fuel boilers with little modification required to the boiler. This is an attractive option for industrial boilers looking to re-power with biomass due to rising gas or coal costs, or for fossil fuel-based power plants for increasing the renewable generation plant, for a relatively lower cost for the cofiring retrofit.

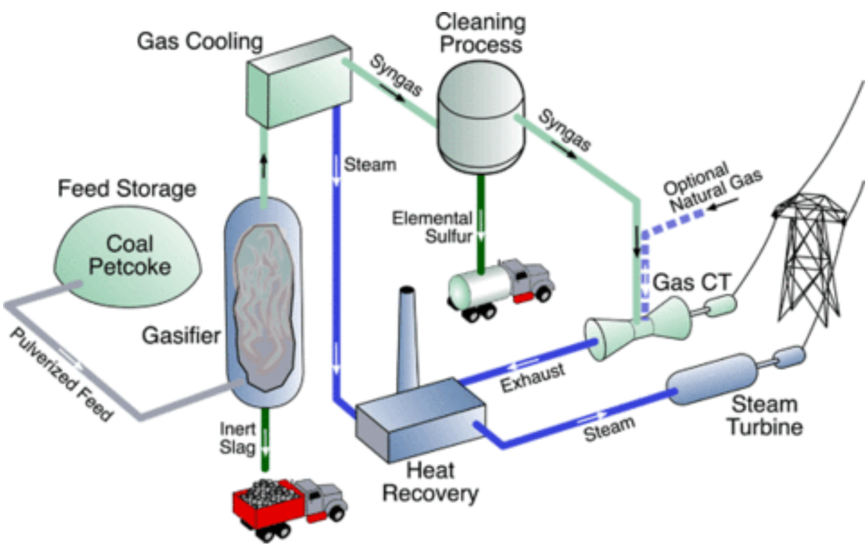

Figure 1.9: Integrated Gasification Combined Cycle power plant [31]

1.3.4. Advantages and Disadvantages of Biopower

The main advantage of power generation through biomass is in relation to the environment: the substitution of fossil fuels, achieved through the upgrade of old coal-fired power plants, and consequent reduction of GHG emissions, represents the greatest potential of this technology, especially in relation to the new emissions standards to be met in the following years in Europe and worldwide. The key principle of the biomass life cycle is that, when growing, plants absorb CO_2, making biomass technology carbon-neutral. Although the process of harvesting, transportation, conversion and use of biomass include some fossil fuel inputs, the overall lifecycle benefits of the supply chain are much better than the utilization of fossil fuels only. GHG emissions for biomass-fired power plants are estimated to be around

15-65% lower than emissions from fossil fuel-based power plants, characterized by 400-1000 gCO_2-eq/kWh, respectively for natural gas and coal, if fast-growing trees are used as feedstock. If wheat straw, rice straw, or corn stovers are used as feedstocks, the emission savings are reduced by 35%. Transporting the biomass over long distances can reduce even more the emissions savings by 15-30% [32]. In the case of IGCC plants, the best results are obtained in terms of reduced environmental impacts. IGCC plants have the lowest CO_2 emissions among coal power plants [33]. An IGCC plant emits around a quarter less CO_2 than a pulverizing coal power plant, which emits around 750 g CO_2-eq/kWh, because of the advantage of removing the CO_2 before the syngas is fed into the gas turbines. Capturing 80% of the CO_2 reduces emission to less than 200 gCO_2-eq/kWh. Moreover, sulfur dioxide and nitrogen oxide emissions are reduced. Finally, co-firing biomass with coal in conventional power plants can help to reduce GHG emissions. The addition of approximately 20% biomass to the mass of the combustion mixture causes the decrease in carbon-dioxide emissions by nearly 11-25% [34]. However, various factors can influence the final life cycle environmental impact of biomass power generation technologies, including water requirements, fertilizer utilization, human labor and transportation fuel used.

Compared with other RES, power generation from biomass is much more flexible than other RES. Regarding the feedstocks, a wide range of wastes, residues and plants grown for energy purposes can be used directly as fuels for heating or cooking, for electricity production, or converted into gaseous or liquid fuels for transport. Moreover, there are many pathways through which biomass feedstocks can be converted into these forms of useful renewable energy, many of them based on well-established and commercially available technologies. Regarding power generation, biomass technology is not affected by the issue of intermittency which is the main limit in relation to solar and wind power plants. This makes biomass power plants capable of providing firm and flexible generation, in terms of both base-load power or peak demand power, increasing their potential in relation to the context of an increased penetration of renewable energy in the generating mix of a country.

The main barriers limiting the implementation of this technology are mainly related to the feedstocks procurement. As summarised by [29], the critical issues in biomass logistics are the specific properties of biomass (e.g. low energy density, seasonal availability and problematic storage requiring further pre-treatment) and factors limiting the supply (e.g. availability and appropriateness of mechanized equipment, inadequate infrastructure to access conversion facilities and markets). These factors make difficult to assure a constant flow of biomass feedstock over the year, necessary for running the power plants, in most cases limiting their size. The main solutions to these issues are the development of advanced densification and other pre-treatment technologies, diversifying procurement geographically and in terms of biomass types, securing sufficient supplies of biomass over a long-term, and the optimization of fuel supply chains from field to plant [29].

1.3.5. Worldwide Biopower Market

Biomass power generation is based on well-established and commercially available technologies, making it accessible and easy to implement worldwide. Most of the biopower plants use direct-fired systems to generate electricity, with the largest ones concentrated in the Nordic countries and the United Kingdom. In the United Kingdom, it is located the largest pure biomass power plant in the world, Ironbridge power plant, with an installed capacity of 740 MW. Globally, biopower capacity is increasing year by year, mainly due to its key feature of being a source of backup and dispatchable electricity compared with conventional RES, with a total of 112 GW installed at the end of 2016. The leading country for electricity generation from biomass in 2016 was the United States (68 TWh), followed by China (54 TWh), Germany (52 TWh), Brazil (51 TWh), Japan (38 TWh), India and the United Kingdom (both 30 TWh) [12]. Although the United States was the largest producer of electricity from biomass sources, according to [35], Europe is the largest biopower market in the world, accounting for 34.7% of the global cumulative biopower installed capacity. Asia-Pacific is the second-largest region with a share of 30.25%, followed by North America, South and Central America, and the Middle East and Africa. The rise in global installed capacity during the last years can mainly be attributed to the installations in China and Brazil. Brazil, the largest overall consumer of electricity and bio-power in Latin America, used almost entirely solid-biomass conversion, with negligible biogas capacity addition. China, on the other hand, installed biomass and biogas plants. The steady growth of the cumulative capacity is expected to continue, to reach 165.2 GW by the end of 2025, with more than 84% of the capacity using solid-biomass conversion technology.

Regarding Europe, bioenergy only represents 18 percent of renewable electricity production, but as intermittency remains an issue, biomass will play a growing role as a backup, dispatchable energy source. A majority of this biopower (60.4 %) comes from CHP plants. On the other hand, CHP plants represent the smallest use for traditional power generation at only 11.7 percent, whereas power-only plants amount to 88.3 percent. Europe's largest producers of electricity from biomass are Germany and the United Kingdom, with respectively 7.6 GW and 5.6 GW of installed capacity, and respectively 52 TWh and 30 TWh of generation. They are in the top five countries generating bioelectricity, together with Italy, around 20 TWh of generation in 2016, and France [36]. Spain set a goal for biopower of 1350 MW of capacity to be installed in the period 2011-2020, in the *Renewable Energy Plan 2011-2020*. In 2014 they had already installed 639 MW, 49% of the target [37]. This plan will increase the renewable generation in the country, together with its competitivity, thanks to the potential of the biomass sector, especially in terms of richness in biomass resources. The country generated around 12.57 TWh of bioelectricity in 2015 and is expected to generate 38.1% of its electricity demand by renewables in 2020, a big share coming from biomass power plants.

Today the debate on EU sustainability criteria for biomass places the sector under scrutiny: depending on the final outcome it may be severely restricted. Nevertheless, biopower will be needed in the future to sustain further ambitious targets for the decarbonization of the power sector in Europe in the coming decades. Biopower also has a role to play as a major source of low-carbon dispatchable power needed as a backup to the erratic generation of other RES, such as wind and solar power [36].

1.4. Hybrid CSP-Biomass Technology

1.4.1. Basic Principles

The basic principle behind the concept of a hybrid power plant is that it is possible to combine two different technologies for generating electricity, compensating the drawbacks of each one in order to improve the overall performance of the power plant and lower the capital costs. As described in the previous chapters, CSP is a mature and attracting technology for the production of electricity and heat from a renewable energy source [38]. However, standalone CSP power plants suffer from intermittent energy output due to day/night cycles and also from reduced irradiation periods during winter, as well as cloudy days or transients [39]. This intermittent nature of solar energy leads to unfavorable solar power system performances and low capacity factor [40]. The integration of a thermal energy storage (TES) system can make CSP dispatchable and increase its energy conversion efficiency and flexibility. However, even with TES the capacity factor of solar power plants is often still low [41]. Furthermore, the integration of efficient heat storage systems (e.g. molten salts, concrete and latent heat) results in a higher specific investment for the solar power plant [40]. In response, many hybrid solar/fossil-fuelled plants are currently in operation or under development to mitigate this issue. As an alternative to fossil fuels, biomass can be an interesting renewable energy option for hybridization [41].

Biomass combustion is also a mature renewable power generation technology, with a large number of power plants in operation worldwide [40]. Biomass power plants are more flexible compared to CSP, and can operate continuously since they only rely on the availability of the biomass feedstock (i.e. the renewable fuel). However, they can have high investment costs, uncertain supply chain security and require bulk transportation [39]. In general terms, larger plants benefit from higher energy efficiencies and take advantage of increasing economies of scale, but encounter difficulties to ensure a sustainable and stable supply of biomass feedstock [42].

Although biomass often exhibits seasonal availability and presents specific logistic and supply constraints, it is complementary, both seasonally and diurnally, with CSP, and this hybridization could contribute to overcome the individual drawbacks of these primary energy resources and allow such plants to achieve either base load or flexible operation [41]. The integration of the CSP with a biomass boiler can improve the flexibility and competitiveness of the power plant, increasing the number of equivalent operating hours and decreasing the size of the solar arrays. On the other hand, the biomass system can benefit from this integration since the required biomass consumption in the hybrid power plant is reduced, thereafter decreasing the risk associated with the biomass supply [40]. In the end, the integrated system is more sustainable and, if correctly designed, can lead to higher efficiencies [38].

Hybrid CSP-biomass power plants consist of two major subsystems [20]:

- The solar field, which concentrates the solar energy onto the receiver, where it is collected by the Heat Transfer Fluid (HTF). As explained in the previous chapters, there are different types of HTF (e.g. water, oil or molten salts), as well as CSP technologies for the collection of the solar radiation. Among these, parabolic trough concentrators are preferred as they represent the most commercially-proven and reliable option. Despite lower concentrating ratios, they have values of annual solar and thermal efficiencies, as well as capacity factor comparable to the other technologies. Moreover, the modularity of PT technology compared to ST allows for more flexibility in the choice of the size of the solar field.

- The biomass co-powering system, with the aim of increasing the temperature of the HTF coming from the solar field to feed the steam boiler, or heating up water to produce steam to run, together with the steam coming from the solar-driven steam boiler, the steam turbine. Available technologies include biomass combustion and gasification, with the former preferred over the latter due to its maturity and reliability. In fact, despite the lower system efficiency compared to conventional gasification and IGCC, the combustion technology is the most widely deployed for power generation due to its economic competitiveness (i.e. lower investment, O&M and labor costs).

It is not a case that, due to the good trade-off between performance and reliability, the only commercially operational hybrid power plant operates with PT technology (i.e. the Termosolar Borges in Lleida, Spain). Despite the advantages highlighted, a lot of work is still required in order to support the market diffusion of hybrid CSP-biomass power plants, as demonstrated by the very limited number of actual installations, which in Europe include the only Spanish example [38].

1.4.2. Plant Configurations

As described in [42], two different configurations are possible for the integration of the biomass (co-powering) system into the CSP power plant. The first configuration, shown in Figure 6, is characterized by the substitution of the backup NG boiler with the biomass boiler, to increase the temperature of the HTF coming from the solar field instead of water, in order to meet the required set-point for the steam boiler. As it happened with the original natural gas boiler, this kind of design requires the biomass boiler to have a very efficient dynamic response in order to adapt its working point to the variability of solar irradiation conditions. For this purpose, the biomass boiler usually includes a rapid response natural gas backup system.

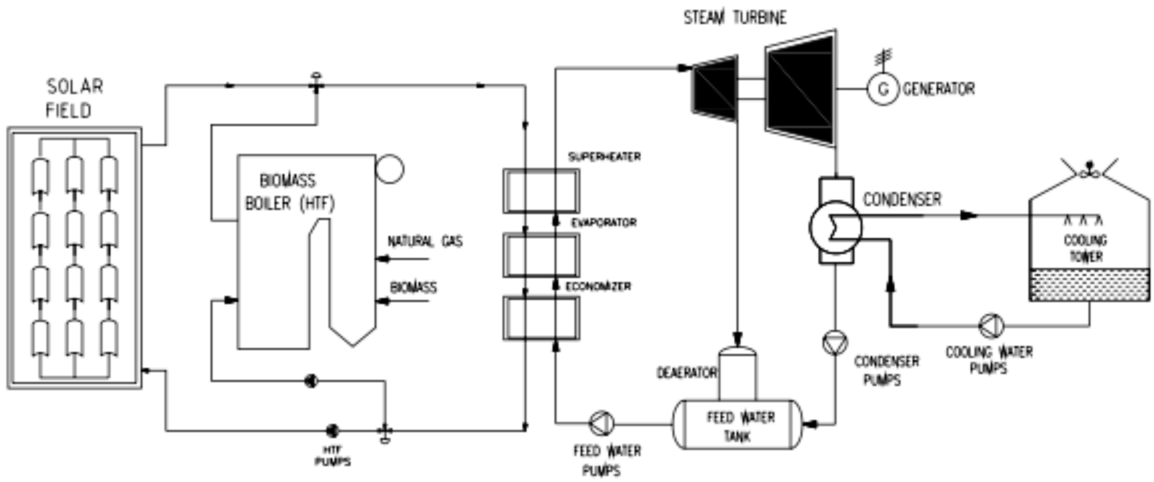

Figure 1.10: : CSP-biomass hybrid configuration where the natural gas boiler has been substituted by a biomass boiler [42]

In the second configuration, shown in Figure 7, both the solar and the biomass systems have the capacity to generate superheated steam. Both streams are connected together for increased energy generation. In order to maintain appropriate steam conditions, the volume of water fed through the biomass boiler is adjusted depending on the solar irradiation and the steam generated by the solar field. The biomass boiler can operate at different capacities to produce, in case of baseload operation, a constant electrical output depending on the solar contribution.

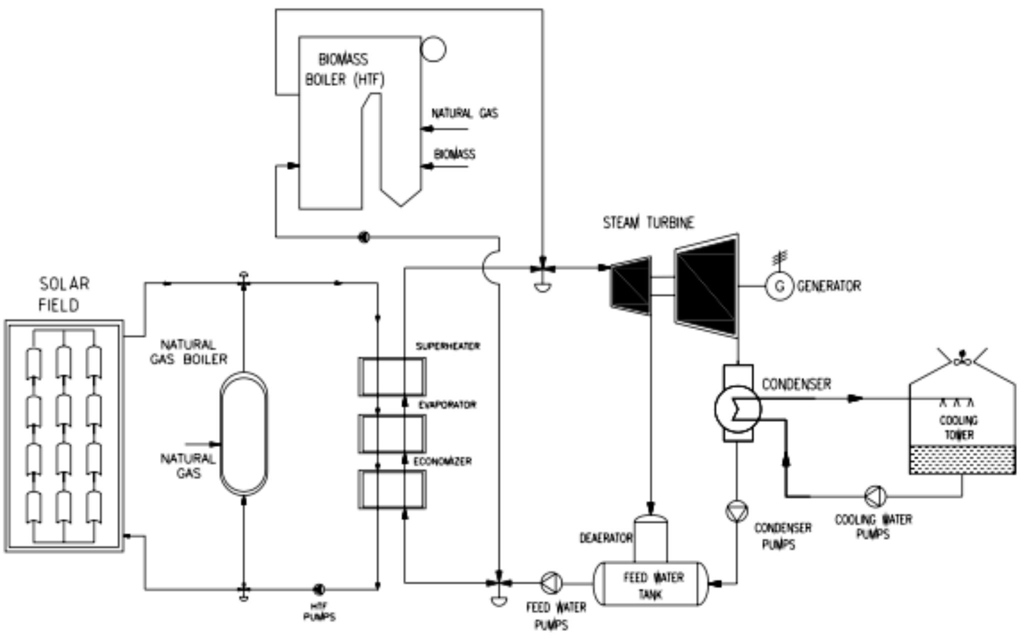

Figure 1.11: CSP-biomass hybrid configuration with CSP and biomass units set in parallel [42]

1.4.3. Advantages and Disadvantages of Hybrid CSP-Biomass

Considering two separate power plants, based on solar or biomass resources, the power output from the solar field of the CSP power plant would occur only during the daytime, since it is closely related to the solar radiation availability. In the case the plant was not provided with a TES system, the power generation would coincide with the solar radiation availability periods. On the other hand, a biomass power plant would generate a constant electrical output and use corresponding biomass resources at a constant rate, but limiting the size of the plant due to the constraints in the supply chain. The integration of the biomass boiler in the CSP power plant, thanks to their complementarity as primary energy resources, lead to the already highlighted advantages of improving the flexibility and competitiveness of the power plant, increasing the number of equivalent operating hours and decreasing the size of the solar arrays. Regarding the biomass system, it can benefit from this integration since the required biomass consumption in the hybrid power plant is reduced, when there is sufficient output from the solar field, thereafter decreasing the risk associated with the biomass supply [40]. At the same time, when no solar radiation is available, especially during night time or transients (e.g. completely cloudy days), the power plant operates in only-biomass mode, generating all the power required. The fact that the biomass boiler can operate at different capacities is extremely positive in relation to the steam turbine, since hybridization allows a continuous operation of the steam turbine, avoiding daily start-ups and shut-downs, thus extending the lifetime of the equipment.

Another important characteristic of a hybrid solar-biomass power plant is the presence of some common types of equipment. The thermal nature of the energy employed in both CSP and biomass combustion power plants make these two processes compatible and complementary [42]. Beside the equipment typical of CSP plants (e.g. solar field, heat recovery boiler, HTF pumping system) and biomass plants (e.g. biomass boiler, biomass feedstock storage and preparation area), some shared types of equipment are [42]: Turbine-generator set, where thermal energy is transformed first into mechanical energy and finally into electricity by means of a power generator. Since the working fluid is the same in both technologies (superheated steam), a unique turbine-generator set may be shared by a hybrid solar-biomass system; Common elements in the Rankine cycle, including not only pipes, valves and control devices, but also the condenser, cooling towers and the deaerator; Common services,such as the feed water, compressed air and gas supplies, electrical devices and infrastructures necessary both in CSP and biomass combustion plants.

Beside the lower space requirements for the solar collectors and reduced biomass supply constraints due to lower fuel input requirements, the modularity of the PT technology, the more flexible operation of the system when modulating the biomass contribution and possibility to obtain dispatchable renewable energy from smart integration of intermittent solar and programmable biomass sources, higher conversion efficiency compared to CSP-only systems at the same plant size (i.e. better use of the solar energy input), there are also some disadvantages. The main drawbacks of a hybrid solar-biomass power plant can be resumed as [43]: selection of a potential site, where not only solar irradiance is good but where there is also a good availability of biomass resources; technical challenges, mainly related to the control mechanism made difficult by the intermittent nature of solar radiation, making difficult to maintain a stable operation, thus reducing system efficiencies and increasing levelized costs; the biomass suppy chain, since one of the greatest challenges of any biomass power plant is the secure and cost-effective supply of large quantities of biomass. Therefore, a primary concern for any large-scale project is to identify or establish an effective biomass supply-chain; economic challenges, mainly related to the high capital costs of the technology. Hybrid solar/biomass plants will become an increasingly attractive option as the price of fossil fuel and land continue to rise and the cost of solar thermal technology falls, becoming more widely deployed [39].

2. Numerical Simulation of Termosolar Borges Power Plant

In the first section of the present report, an extensive introduction comprehensive of a literature review has been presented regarding the main technologies utilized for CSP and Biomass power generation, including both design and operational aspects of each of them. Moreover, the hybrid CSP-biomass technology has been introduced, in order to understand the main operating principles and key advantages of combining the two technologies together for generating renewable electricity. In this section, the focus is put on the description and numerical simulation of the only existing CSP-biomass power plant in the World: the Termosolar Borges operating in Lleida, Spain. First, the main characteristics of the power plant are presented, including the location and orientation as well as its layout and operating principle. Then, the mathematical models of the different power plant components are described, in order to understand how they work and how the power plant works as a whole, followed by a brief overview of the simulation environment based on *TRNSYS 16* software. Finally, the simulation results are presented regarding some typical days of operation (e.g. sunny/cloudy day). The results obtained are compared with the performance parameters of the reference power plant, in order to check the consistency of the model and validate its outcomes.

2.1. Power Plant Description

For this project, the technology of parabolic cylindrical concentrators has been chosen. The concentration of the solar radiation takes place by means of collectors of cylindrical-parabolic form. Through the focal axis of said collectors passes a conduct through which circulates a thermal fluid (oil) that, through the incidence of solar radiation, is heated. Next, the oil, through a duct system, passes from the solar field to the heat transfer system, where steam is produced at high pressure by passing the oil through three heat exchangers connected in series (water preheater, steam generator and steam superheater). The oil acts as a means of heat transfer between the solar field and the power block of the Rankine cycle, heating up in the solar collectors and cooling down when producing the steam required by the alternator. The produced steam is sent to the power block, where it is expanded in a steam turbine that drives the corresponding generator of electricity. Through this process, the solar radiation collected and concentrated by the solar field is converted into electricity and then proceeds to its distribution through the general electrical network. The cold oil that comes out of the last heat exchanger is returned to the solar field to be heated again.

So far the design coincides with that of a conventional installation without hybridization. This type of plant usually has auxiliary boilers powered by natural gas, for starting, stopping and maintaining the oil temperature. The Termosolar Borges plant is innovative given that it is the first plant in the world that incorporates the hybridization of the solar field with biomass boilers. This combination allows that in the hours when solar radiation is not available (nights) or when it is not enough, the thermo-solar unit is complemented by biomass units that burn wood of forest origin [44].

Figure 2.1: Termosolar Borges power plant: deposit of forest residues

2.1.1. Location and Orientation

The choice of the location is a key decision variable in the process of developing a power plant based on CSP technology. In fact, the solar resource varies a lot with the latitude and can strongly affect the producibility of the power plant, requiring an accurate selection of the type and size of concentrating solar technology to be implemented. Most of the European CSP power plants in operation are typically located within the average DNI range of 1800–2000 kWh/m^2/year [38]. This is mainly due to the fact that solar-only power plants rely on the solar resource as the unique source of thermal energy, so the higher the direct normal irradiance in the region, the better the power plants will perform. However, DNI below that range may be useful for hybrid technologies, as long as the availability of the biomass feedstock is guaranteed. In fact, hybridization can optimize the power plant output by optimally exploiting the moderate solar resource, at the same time limiting the biomass resource usages when solar insolation is available. Indeed, the world's only hybrid solar-biomass power plant is located in North East Spain (Lleida), within the region of average DNI 1600–1800 kWh/m^2/year. All other CSP power plants in Spain are located in southern Spain [38].

Regarding the orientation of the PTs which compose the solar field, it is demonstrated that the north-south axis harvests more energy in summer where east-west produces more in winter [45]. Due to operational issues, mainly the shut down of the biomass units during summer months, the axis of the PTs were oriented north-south, so that the thermal energy delivered daily during summer months is almost three times more than in winter months, leading to a higher global efficiency of the plant all over the year.

Figure 2.2: Termosolar Borges power plant: aerial view of the with main sections

2.1.2. Plant layout

A schematic of the Termosolar Borges is shown below in figure 2.4. The three main blocks can be seen from left to right: the solar field and biomass units, forming the thermal oil loop, the heat transfer system, and the power block including the refrigeration circuit and condenser. Also, the main temperatures and pressure of the thermal cycle are highlighted.

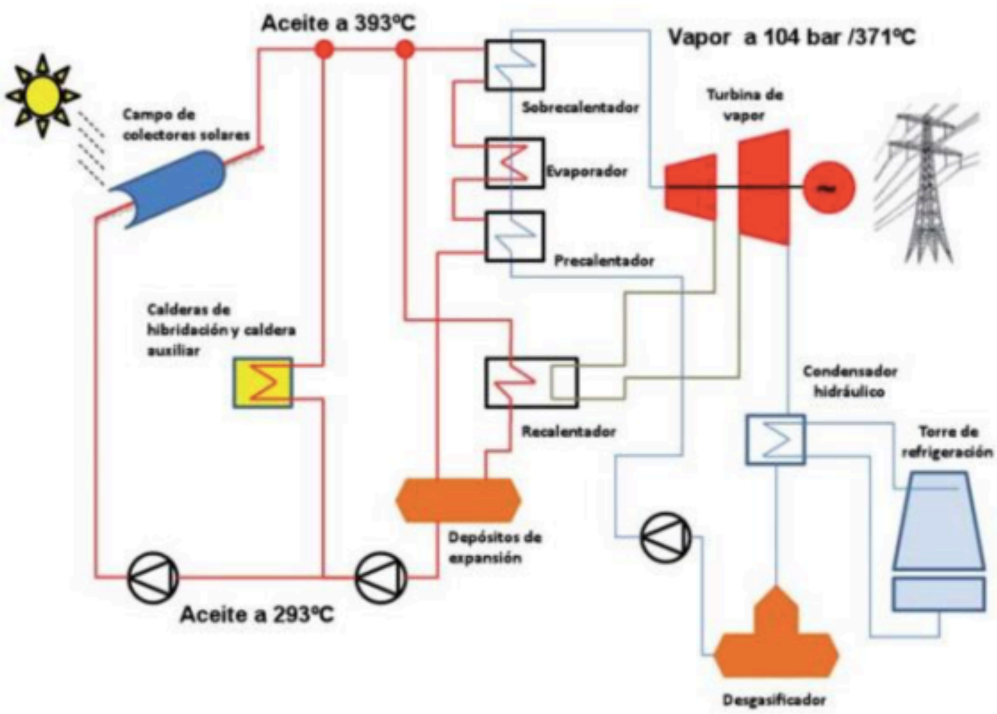

Figure 2.3: Termosolar Borges power plant: schematic with main components

Solar Field

The installation consists of a solar field located in 183120 m^2 that has been subdivided into 4 subfields connected in parallel. In total there are 336 collectors of 100 m length each, grouped in 56 loops, which convert direct solar radiation into thermal energy through the heating of the thermal oil that circulates inside the absorbent tubes of the collectors. Each collector consists of 8 units of 12 m in length and 5.77 m in diameter with parabolic shape, the collector is supported on the ground by 9 pillars one of which is motorized to provide the system with the necessary movement to track the sun so that the incident radiation is always concentrated in the tube through which the oil circulates. The receiver, or absorbent tube, is in charge of converting the energy of concentrated sunlight into thermal energy of the heat-carrying fluid [44]. In the case of this project, the chosen model was the UVAC 2010, supplied, as for the rest of the solar field components, by *Siemens* subsidiary *Siemens Sunfield* [46].
The thermal interconnection between the solar field and the power cycle is carried out through the oil flow. The cold oil from the power cycle is directed to the field of collectors where it is heated from about 293 °C to a temperature of 393 °C. Alternatively, the oil can be directed to the biomass boilers that will serve as support during the nights and days of lower radiation [44].

Figure 2.4: Termosolar Borges power plant: solar field

Biomass Unit

The biomass unit, used as an alternative and a support to the solar field for heating the thermal oil, is formed by two twin boilers that have a chip feed system, which elevates the sliver produced from wood logs to the loading mouth. This feeding system introduces the biomass in the grills which have an advanced system to allow the biomass to advance inside the boiler while the combustion takes place. Above the grills, there is a combustion chamber where two natural gas burners have been installed, which alternatively can provide the necessary thermal energy instead of the biomass if necessary [44]. Both the biomass boilers

integrated with gas burners, shown in Figure *2.5,* were provided by *INTEC Energy* [47]. The available biomass is a mix of forest waste and energy crops [48].
The transfer of energy to the thermal oil is carried out in such a way that the boiler fumes at a temperature of 900 °C flow through the radiation chamber, where begins the transfer of the energy contained in the fumes to the thermal oil circulating inside a serpentine; later in the convention chamber the transferring process of thermal energy is concluded. Afterward the still hot fumes circulate through a heat recovery system preheating the combustion air, and finally they are taken to a set of emission treatment elements (cyclones and electro-filters) to ensure optimal levels, well below of those marked by legislation. This unit is capable of heating the thermal oil to a temperature of 393 °C to send it later to the oil-water heat exchange train where the superheated steam required by operating the turbo-alternator is generated. As mentioned above, it can work independently of the solar field or even in a complementary way [44].

Figure 2.5: Termosolar Borges power plant: biomass unit

Power Block

The thermal oil gives its energy to a water cycle generating superheated steam. It is done in various cascade equipment to optimize the performance of this entire process. Firstly, the hot oil from the solar field and/or from the biomass boilers feeds the superheater, where the water vapor temperature rises up to 371 °C, then it is introduced into the evaporator where steam is generated from condensates recirculated at a pressure of 104 bar, finally the oil flows through the preheater where the condensates are heated up to the evaporation temperature. In this way, the energy contained in the oil is optimized leaving the steam train at 293 °C and returning to the solar field/biomass unit to be heated again [44].

The superheated steam feeds a *MAN Diesel & Turbo* MARC-R steam condensation turbine, shown in Figure 2.6, an interim heating turbine with two casings. Constructed out of a MARC2-B01 backpressure type turbine and a MARC6-C04 condenser type turbine, the MARC-R forms part of the MARC, short for *Modular Arrangement Concept*. The construction increases the thermodynamic efficiency, thereby enhancing the overall efficiency of the power plant considerably [47].
Once it has gone through the first stage, the steam with a much lower pressure is reheated to 371 °C by a reheater that takes a small part of the thermal oil from the solar field and/or biomass unit. This superheated medium pressure steam feeds the second stage of the turbine. Both turbines are integral with the same axis and move the alternator previous reduction of the speed of rotation until the 1500 rpm. The total installed power is (24.29) 25 MW, (with the total energy discharged to the power grid of 98,000 MWh/year) [44].

Figure 2.6: Termosolar Borges power plant: HP and LP steam turbines

Auxiliaries

This installation has a series of auxiliary units necessary for the correct operation of the plant. Some of these are the water treatment plant, the firefighting unit and the generator group. Moreover, it is important to highlight the auxiliary natural gas boiler: the function of this auxiliary boiler is that of thermal input to the thermal oil system in the start, stop and above all phases for the maintenance of the temperature of the thermal oil in periods of stoppage, as it freezes below of 15 °C. It has a power of 4.4 MW and a steam generation capacity of around 3 tonnes/hour at 15 bars. A specially designed control system balances the three to maintain stable generation. With the change of regulations and tariff system, this unit does not start operating habitually to optimize the economic performance of the plant [44].

2.1.3. Operating Principle

The hybridized configuration of the power plant allows a continuous power generation, achieved in different ways depending on the time of day, the weather and the season of the year. The plant works producing electricity between 50% and 100% of the Turbine Load Point (TLP). During daylight in winter, the plant operates with solar energy that will be complemented with biomass, focusing the turbine to its maximum load (and performance), while at night, the plant operates only with biomass but with a TLP of 50%. This is mainly due to the availability of biomass feedstock: if enough biomass was available in the area, the plant would be able to operate at 100% TLP also during night time. The thermal oil (HTF) flows constantly, with an increase in temperature of 100 °C in the thermal block [48]. So, at any moment a constant flow of HTF of at least 50% of the rated mass flow is maintained, in order to operate the power block at least at 50% of its rated power, regardless the time of the day. A scheme of the power plant working conditions can be seen in Figure 2.7.

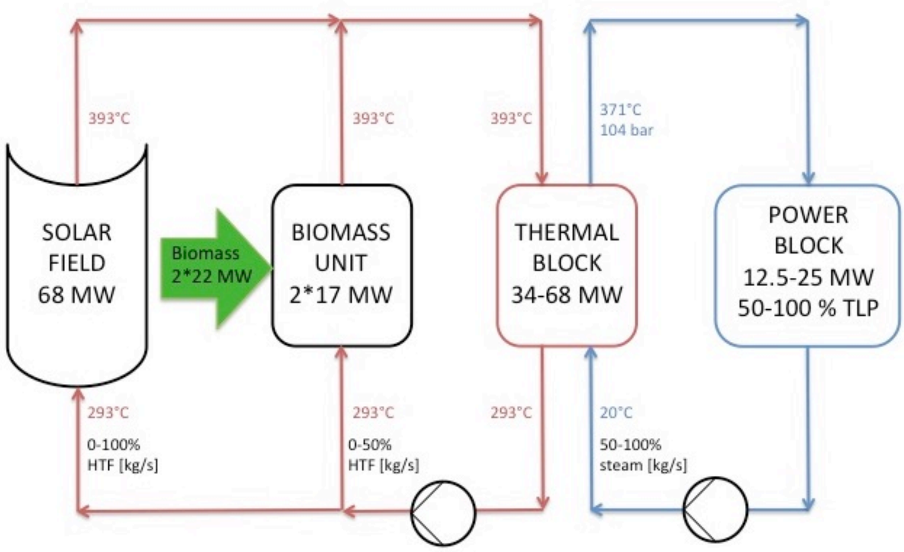

Figure 2.7: Termosolar Borges power plant: operating principle

The use of biomass facilitates the "sun tracking", in the sense that the control system regulates the biomass unit in order to complement the process of heating the thermal oil provided by the solar field, without overheating it (thermal energy absorbers might be required during periods of high irradiation due to the inertia of the biomass unit). Hybridization allows to transcend the clouds affections and lowers any kind of potential hydraulic imbalance in the solar field. In the transition between night time and daytime, an increasing part of the thermal oil is heated up from the solar field until it reaches the required temperature difference, modulating the process with biomass and natural gas. So the natural gas, unlike the rest of CSP power plants in the world, is used only as a residual resource of support in implementations underway. The plant operates 11 months per year, excluding December for maintenance issues. The operational period is divided in 8 months on hybridization mode, during winter time, and 3 months on solar mode, in summer, to not exceed the quota for biomass burning that establishes the regulations (i.e. 50% power generation from biomass) [48].

2.2. Power Plant Modeling

In this section, the Termosolar Borges hybrid power plant is modeled, with the aid of some computer programmes. For the gross capacity of 25 MW_e, *MATLAB* software is used to model the power plant at reference weather conditions, especially for determining the different state points of the steam cycle, including properties such as pressure, temperature and specific enthalpy. The outputs of the code are then used as reference values in *TRNSYS* for the modeling and simulation of the power plant also at off-design weather conditions. In the *TRNSYS* simulation, the components taken from the library of Solar Thermal Electric Components (STEC) are used for both solar and conventional power cycle elements, in addition to the built-in *TRNSYS* components. First, the methodology adopted for the modeling of the power plant is presented, both from a technical and economic point of view, together with the main assumptions made, followed by the mathematical models of the main components of the plant. These components are described in order to understand how they work and how the power plant works as a whole from a more scientific point of view. Then a brief overview of the simulation environment based on *TRNSYS 16* software is presented, in order to introduce its main features, especially for those not familiar with this particular kind of simulation environment. The simulation results regarding some typical days of operation (e.g. sunny/cloudy day) are presented in the following section.

2.2.1. Methodology and Main Assumptions

In the modeling section, the starting point is the analysis of the Rankine reheat power cycle, in order to identify the different state points of the Rankine reheat cycle and their main properties including pressure, temperature and enthalpy. *MATLAB* software is used to model the plant at nominal conditions, and the results obtained are shown in Table 2.1. These results are showed for each point of the power cycle and, for the purpose of better identifying them, a detailed block diagram of it is shown in Figure 2.8. The technical parameters of the main components of the plant are identified at this point, in order to correctly model its operation, and are shown in Table 2.2. In particular, for the biomass unit and steam turbines, representing this hybrid power plant a very unique application, the technical characteristics were obtained directly from the manufacturers [49] [50]. After having properly modeled and simulated the power cycle, knowing the rated mass flow rate of steam, it is possible to concentrate on the thermal block determining the required mass flow rate of thermal oil, which is in charge of delivering the thermal power to the steam generator. This is done focusing on the analysis of the solar field and biomass unit components, which are in charge of elevating the temperature of the HTF, and represent the real source of thermal power. Regarding the fraction of thermal oil directed to the reheater, this is set to be 14%, as given in [49], for the purpose of reheating part of the steam coming from the HP steam turbine and directed to the LP steam turbine.

When all the components of the power plant have been analyzed, by properly identifying their input and output parameters, each one is modeled with the correspondent component chosen from the *TRNSYS* library, and then linked one to the others in order to reproduce the exact layout of the plant. The results obtained from the initial analysis are used at this point for setting the input parameters for the different *TRNSYS* components. For instance, the

working pressures and temperatures of the steam generator and turbines are set, as well as more technical parameters, such as the aperture area of the solar field among others.
Since *TRNSYS* software is used for simulating the performance of the power plant at each hour during an entire year, also at off-design weather conditions, and generating - the power plant - in these weather conditions less power than the rated capacity, it has to be highlighted the importance of using a consistent weather file in relation to the location of the plant, to perform a valid yearly simulation. For the particular case of the Termosolar Borges, monthly average daily values of global horizontal solar radiation are taken from the ADRASE website [51], managed by the CIEMAT research group of the Spanish Ministery of Economy, Industry and Competitiveness.

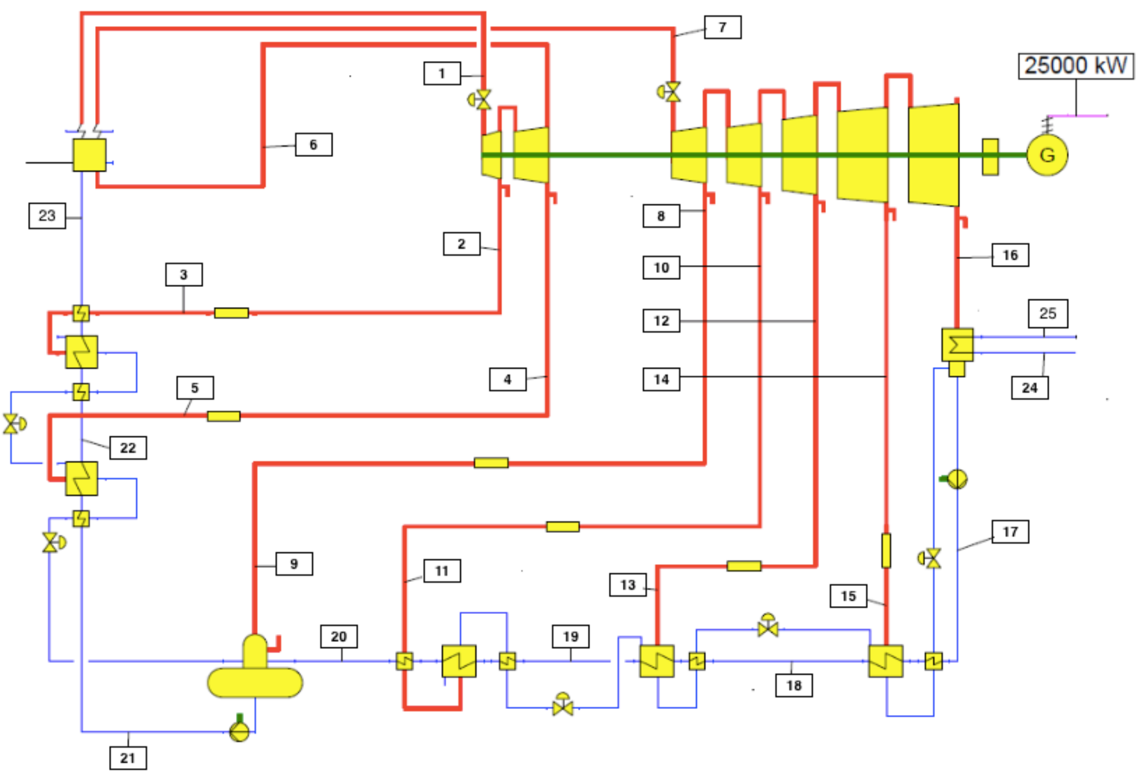

Figure 2.8: Termosolar Borges power plant: Rankine reheat cycle [49]

Monthly average values of dry bulb temperature, relative humidity and wind are taken from [52], and specific humidity values are calculated from the previous using the humidity calculator available at [53]. A resume of these calculated weather data is showed in Table 2.3. The *Weather Data Processor* component (Type 54a) is used to generate hourly weather data given these monthly average values of solar radiation, dry bulb temperature, humidity ratio and wind, to make them available to other TRNSYS components.

Table 2.1: Properties of the different state points of the rankine reheat steam cycle

State Point	p [bar]	T [°C]	h [kJ/kg]	m [kg/hr]
1	100.00	375.00	3018.7	107345
2	43.50	275.79	2872.8	8323
3	41.32	272.78	2872.8	8323
4	25.00	223.94	2771.2	7187
5	23.75	221.23	2771.2	7187
6	25.00	223.94	2771.2	91835
7	22.50	375.00	3189.4	91835
8	12.00	300.21	3047.4	5726
9	11.04	299.05	3047.4	5726
10	5.00	202.35	2860.2	5108
11	4.75	201.74	2860.2	5108
12	2.00	120.23	2699.3	5579
13	1.90	118.62	2699.3	5579
14	0.50	81.35	2508.8	5504
15	0.47	80.07	2508.8	5504
16	0.06	36.18	2326.0	69919
17	12.14	36.29	153.0	86110
18	11.79	77.07	323.5	86110
19	11.44	115.62	485.8	86110
20	11.04	148.35	625.4	86110
21	110.70	186.30	795.9	107345
22	110.40	218.23	938.2	107345
23	110.00	250.15	1086.6	107345
24	5.00	28.00	117.8	11114112
25	4.95	31.28	131.5	11114112

Table 2.2: Monthly average values of global horizontal solar radiation, dry bulb temperature and specific humidity in Lleida (Spain

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$I_{g,horizontal}$ [kWh/m²]	2.3	3.4	4.8	5.9	7.3	7.8	7.9	6.6	5.3	3.5	2.1	1.6
T [°C]	5.3	7.9	10.8	13.2	17.3	21.4	24.7	24.5	20.7	15.3	9.3	6.0
Specific Humidity [kg_{water}/kg_a]	39.4	47.7	56.2	64.8	82.2	108.4	134.9	134.8	108.1	73.5	48	39.5

Table 2.3: Technical parameters of the main components of the 25 MW_e Termosolar Borges power plant

Parabolic Trough		**Biomass Unit (2 x Biomass Boilers)**	
Length of SCA	96 m	Grate Firing Capacity	2 x 22 MW_{th}
Aperture Width of SCA	5.77 m	Boilers Efficiency	77%
Focal Lenght of SCA	2.17 m	Biomass Feedstock LHV	3.05 kWh/kg
Row Spacing	15 m	Inlet Temperature Biomass Unit	293°C
Total Field Area	183120 m^2	**Super Heater/Reheater**	
Inlet Temperature Solar Field	293 °C	Source Side Inlet Temperature	393°C
Cleanliness Solar Field	0.95	Superheater Source Side Flow Rate	916835 kg/hr
Specific Heat HTF	2.303 kJ/kgK	Superheater Load Side Inlet Temperatur	311°C
Density HTF	900 kg/m^3	Reheater Source Side Flow Rate	149252 kg/hr
Wind Speed Limit for Tracking	13.5 m/s	Reheater Load Side Inlet Temperature	223 °C
Preheater		**Evaporator**	
Source Side Inlet Temperature	311°C	Source Side Inlet Temperature	376°C
Load Side Inlet Temperature	250°C	Load Side Inlet Temperature	311°C
Load Side Flow Rate	107345 kg/hr	Load Side Outlet Pressure	100 bar
Turbine		**Condenser**	
Turbine Outlet Pressure (HP stage)	25 bar	Cooling Water Inlet Temperature	28°C
Turbine Outlet Pressure (LP stage)	0.060 bar	Cooling Water Mass Flow Rate	11114.1 ton/hr
Turbine Inlet Flow Rate (HP stage)	107345 kg/hr	Temperature Increase Cooling Water	3 °C
Turbine Inlet Flow Rate (HP stage)	91835 kg/hr	Inlet Steam Enthalpy	2368.5 kJ/kg
Turbine Inlet Enthalpy (HP stage)	3018.7 kJ/kg	Steam Mass Flow Rate	69919 kg/hr
Turbine Inlet Enthalpy (LP stage)	3187.5 kJ/kg	Condensing Temperature	36 °C
Design Inner Efficiency	80%	Condensing Pressure	0.060 bar

The data are generated in a way that their associated statistics are approximately equal to the long-term statistics at the specified location. In the end, a Typical Meteorological Year (TMY) is generated for Lleida. A *Solar Radiation Processor* component (Type 16a) is used to process the global horizontal radiation read from Type 54a and calculate the solar angles (i.e. solar azimuth and zenith) for a fixed surface at the latitude of Lleida. The obtained yearly DNI is about 1782 $[kWh/m^2\ year]$, very close to the 1800 $[kWh/m^2\ year]$ observed at the plant location. Alternatively, the PVGIS tool can be used for generating a TMY file. These data are of particular importance for the *Parabolic Trough Field* component (Type 397), since the thermal power generation from the solar field relies entirely on the available solar radiation at each hour of the day.
The simulation is performed in *TRNSYS* and the results are obtained on a monthly and annual basis, as well as presented for some typical days of operation (e.g. sunny/cloudy day, night). Electricity generation and thermal powers generated from the solar field and biomass unit, DNI and heat gain, water consumption are the main results obtained immediately from the simulation. Other parameters, such as the capacity factor or the biomass consumption, are calculated using the relative formulas. For the biomass consumption $\dot{M}_{raw\ biomass}$ in particular, the following equation is applied

(1) $$\dot{M}_{raw\ biomass} = \frac{\dot{E}_{el,bio}}{LHV_{raw\ biomass} \cdot \eta_{el}}$$

where $\dot{E}_{el,bio}$ is the annual electrical power generated using the biomass unit as the source of thermal power, $LHV_{raw\ biomass}$ is the heating value of the raw biomass, and η_{el} is the electrical efficiency of the cycle. For calculating the electricity generation from the solar and biomass resources alone, and better assessing the contribution of the two in the final electricity generation, two other *TRNSYS* projects are created, including all the same components and characteristics as the hybrid power plant, but only one between the solar field and the biomass unit. Also, the properly designed control system implemented in the simulation of the hybrid power plant is maintained, so that, in the independent simulations, the generation from the solar field or biomass unit is exactly the same as if the two were operating together in the hybrid plant. The final total electricity generation can be obtained either by running the main project or as the sum of the electricity generations from the two subsystems alone. The second option is preferred, and the following equation applied:

(2) $$\dot{E}_{el} = \dot{E}_{el,sf} + \dot{E}_{el,bio} + \dot{E}_{el,ng}$$

where $\dot{E}_{el,sf}$ and $\dot{E}_{el,bio}$ are respectively the electricity generations from the two independent power plants having the solar field or the biomass unit as the unique sources of thermal power. The term $\dot{E}_{el,ng}$ refers to the part of the electricity generation coming from the additional natural gas boilers used during the summer months, period in which the biomass unit is turned off, to support the solar field for heating the HTF. Due to the complexity of modeling the natural gas boilers, being these used only for superheating the HTF during transient periods of low solar radiation during the day, this electricity generation is assumed to be a fixed value (around 10200 [kWh/year]) as reported in [54] and constantly divided between the three months of July, August and September. Consequently, the $\dot{E}_{el,bio}$ is considered to be the annual generation minus the summer months, and the equation applied in this case is

$$\dot{E}_{el,bio} = \dot{E}_{el,bio-6554} - \dot{E}_{el,bio-4368} \quad (3)$$

where $\dot{E}_{el,bio-6554}$ and $\dot{E}_{el,bio-4368}$ are respectively the electricity generations from the independent power plant having the biomass unit as the source of thermal power at the hours 6554 and 4368, which correspond to the shutdown period of the biomass unit from the 1st of July to the 31st of August. In the end, the total electricity generation is also multiplied for a factor of 0.9, which has been found to be the electricity gross to net factor for the Termosolar Borges, which accounts for the electricity consumption of the pumps circulating the steam and the HTF during the yearly operation.

Cost Analysis

Besides the annual operational results, some economic parameters are also calculated in order to make more complete the analysis of the simulated power plant. In the cost analysis, two different parameters are analyzed: the investment costs and the levelized cost of electricity (LCOE). Both parameters are calculated for two independent power plants based respectively on CSP and biomass technologies, in order to assess the cost of implementing only one of the two technologies alone, and for the hybrid power plant, taking into account the fact that in this case some components are shared during operation. The motivation behind this approach is that, at the moment of analyzing the economic results of the simulated hybrid power plant, it will be easier to identify the benefits, with respect to the increased costs, of choosing the hybrid configuration instead of only CSP or only biomass one. For the calculation of the investment costs, the cost of the main components of the power plants is determined in order to obtain in the end the total investment cost of the plants based on each one of the technologies, and the specific investment cost in euros per kilowatt of installed gross capacity. Contingencies ($f_{conting}$) are accounted as a percentage of 7% of the total cost of the components, and form with them the *total direct costs*. EPC (engineer-procure-construct) and owner costs ($f_{EPC\ \&\ owner}$) are accounted as a percentage of 11% of the total cost of the components. No project financing and land costs are considered. These percentages were found to be typical values, and are the same used by *System Advisory Model (SAM)* programme in the simulation of projects based on the two technologies considered in this work [53]. The characteristic components of a CSP power plant are considered to be the solar field, the heat recovery steam generator (HRSG) and the HTF system, while for a biomass power plant they are the biomass treatment unit and the biomass boiler. The other components, considered as the shared ones in the hybrid CSP-biomass configuration, are the turbine-generator set, including the condenser, cooling tower and deaerator, the balance of plant (BOP) components such as the electrical devices and pumps, and the civil works required for building the infrastructures necessary in both CSP and biomass power plants. The specific costs of these components are reported in Table 2.4, per m^2 of solar field extension or kW of installed gross capacity. All the values are taken from [55], a *SAM's* costs report which include the updated costs for parabolic trough solar fields and biomass combustion power plants, and properly adjusted in the case of the hybrid configuration.

Table 2.4: Specific cost of the main components of the 25 MW_e Termosolar Borges power plant

C_{sf} [€/m²]	250
$C_{treatment\ unit}$ [€/kW]	600
C_{boiler} [€/kW]	1200
C_{HRSG} [€/kW]	400
C_{HTF} [€/m²]	80
$C_{turbogen}$ [€/kW]	400
C_{BOP} [€/kW]	120
$C_{civil\ works}$ [€/m²]	50

The equations applied to calculate the total investment costs in the three different cases of the CSP, biomass and hybrid power plants are the following:

(4) $$C_{inv,sf} = \frac{C_{sf}+C_{HRSG}+C_{HTF}+C_{turbogen}+C_{BOP}+C_{civil\ works}}{(1-f_{conting})+(1-f_{EPC\ \&\ owner})}$$

(5) $$C_{inv,bio} = \frac{C_{treatment\ unit}+C_{boiler}+C_{turbogen}+C_{BOP}+C_{civil\ works}}{(1-f_{conting})+(1-f_{EPC\ \&\ owner})}$$

(6) $$C_{inv,hybrid} = \frac{C_{sf}+C_{HRSG}+C_{HTF}+C_{treatment\ unit}+C_{boiler}+C_{turbogen}+C_{BOP}+C_{civil\ works}}{(1-f_{conting})+(1-f_{EPC\ \&\ owner})}$$

In the end, a sales tax of 5% is applied to the total direct costs and added to the total investment cost. This sales tax form part of the *total indirect costs* together with the EPC and owner costs.

For the calculation of the LCOE, the following general equation is applied

(7) $$LCOE = \frac{C_{inv} \cdot \alpha + C_{o\&m} + C_{dec} \cdot \beta}{Q_n}$$

where C_{inv} represents the total investment cost, calculated using the previous equations for the three cases of the different technologies, $C_{o\&m}$ represents the operation and maintenance costs, C_{dec} represents the decommissioning costs, assumed as 10% of the total investment costs, and Q_n represents the net electricity generated by the power plant in the first year of operation. A degradation rate is applied to the electricity generated in years after the first one, to account for a decrease in the efficiency of the plant. Regarding α and β, they are respectively the annualization factor and discount factor, calculated using the following equations

(8) $$\alpha = \frac{(1+d)^n \cdot d}{(1+d)^n - 1} \text{ , } \beta = \frac{d}{(1+d)^n - 1}$$

In the end, the equation (7) can be further developed and simplified, to better highlight the annual project costs involved in the operation of the power plant. The equations applied for to calculate the LCOE in the three different cases of the CSP, biomass and hybrid power plants are the following

(9) $$LCOE_{sf} = \frac{C_{inv,sf} \cdot \alpha + C_{o\&m,fix} + C_{o\&m,var} + C_{ng} + C_{water} + C_{dec} \cdot \beta}{Q_n}$$

(10) $$LCOE_{bio} = \frac{C_{inv,bio} \cdot \alpha + C_{o\&m,fix} + C_{o\&m,var} + C_{ng} + C_{bio} + C_{dec} \cdot \beta}{Q_n}$$

(11) $$LCOE_{hybrid} = \frac{C_{inv,hybrid} \cdot \alpha + C_{o\&m,fix} + C_{o\&m,var} + C_{ng} + C_{bio} + C_{water} + C_{dec} \cdot \beta}{Q_n}$$

Regarding the annual costs for natural gas, biomass and water, expressed in the equations as C_{ng}, C_{bio} and C_{water}, they are simply obtained multiplying the consumption of the primary resource in year *n* for the relative price for kWh, tonne or m^3. In particular, for the biomass feedstock (a mix of forest waste and energy crops) it was assumed the price per dry tonne reported in the *Plan de Energias Renovables 2011-2020* [56], in the 45% humidity case and for low transportation costs due to the local availability. For the O&M costs for labor and equipment two other terms are introduced: $C_{O\&M,fix}$, which accounts for a fixed annual cost proportional to the power plant's rated capacity, expressed in [€/kW year], which includes labour, scheduled maintenance, insurance, routine component/equipment replacement (for boilers, feedstock handling equipment etc.); $C_{O\&M,var}$, which represents a variable annual cost proportional to the power plant's total annual electricity generation, expressed in [€/MWh$_e$], including non-biomass fuel costs such as ash disposal, unplanned maintenance, equipment replacement and incremental serving costs. Table 2.5 shows an overview of these annual costs, which are in part taken from [55] and in part assumed basing on the particular simulation performed.

Table 2.5: Annual costs and operational parameters for the 25 MW_e Termosolar Borges power plant

N [years]	25
d [%]	5.5
degradation rate [%/year]	0.5
C_{ng} [€/kWh]	0.03
C_{bio} [€/dry tonne]	70
C_{water} [€/m^3]	0.0465
$C_{O\&M,fix,sf}$ [€/kW year]	53
$C_{O\&M,fix,bio}$ [€/kW year]	160
$C_{O\&M,var}$ [€/MWh_e]	3.2

The fixed O&M costs of larger plants are lower per kW due to economies of scale, especially for labor. So, in the case of the upscaled 50 MW power plants, they are considered as 80% of the fixed O&M costs of the reference case. The same reasoning, based on the concept of economies of scale, applies to the capital costs, which will be increased by a factor of 1.8 in the case of the upscaled plants. The values of the different economic parameters involved in the calculation of the total investment costs and LCOE will be defined in the different cost analysis sections of the simulation results, since they may change depending on the particular characteristics of the considered power plant. These values are typical ones and are the same used by *SAM* programme in the simulation of projects based on the two technologies considered in this work [53]. Moreover, it must be specified that the cost of the components refer to the year 2015, so close to the period 2011-2013 in which the Termosolas Borges was commissioned and constructed, with relatively higher prices different from the current ones. *SAM* programme is used to validate the obtained results and check the deviation from reference values of similar power plants. Moreover, some example of the calculations taken from the excel files, developed and used for the cost analysis, will be put in the *Annexes* section.

2.2.2. Mathematical Models

In order to understand the mode of operation of the different components which form the power plant, it is necessary to introduce the mathematical models which describe the thermodynamics and physics behind them. This is done in this chapter, presenting the mathematical models of the main components directly taken from the *TRNSYS* library, which report, for each component, the equations which describe their working principles. These equations are the same applied by *TRNSYS* software when simulating the performance of the power plant and its components starting from the inputs provided by the user. The main components here described are the solar field, the biomass unit and the power block. In addition, it is provided a brief explanation of the control system implemented in the simulation for the regulation of the thermal oil (HTF) feeding the heat recovery steam generator (HRSG). In fact, for keeping the power plant in constant operation, it is crucial to assure a constant flow of HTF to the HRSG, in order to generate steam and run the Rankine cycle.

Solar Field

The modelization of the solar field is done through the "parabolic trough" (type 396) of the *TRNSYS STEC Library*. It calculates the demanded mass flow rate of the thermal oil (HTF) to achieve a user-defined outlet temperature (T_{out}), set to 393°C, by

(1)
$$\dot{M} = \frac{\dot{Q}_{net}}{C_{p,htf} \cdot (T_{out} - T_{in})}$$

using some other equations to calculate the efficiency of the collector field, as well as the net thermal power delivered. The efficiency of the solar field is calculated using the following equation, an integrated efficiency equation to account for the different fluid temperatures at the field inlet and outlet of the collector field [57],

(2)
$$\eta_{sf} = K \cdot M \cdot Sh \left[A + B \cdot \frac{\Delta T_{out} + \Delta T_{in}}{2}\right] + (C + Cw \cdot WS) \cdot \frac{\Delta T_{out} + \Delta T_{in}}{2 \cdot DNI} + D \cdot \frac{\Delta T_{out} \cdot \Delta T_{in} + \frac{1}{3}(\Delta T_{out} - \Delta T_{in})^2}{DNI}$$

This is the absorber efficiency equation in which the coefficients A, B, C, Cw and D are empirical factors describing the performance of the collector. The factor K is the incident angle modifier, M considers end losses and Sh considers shading of parallel rows. Evaluation of these parameters is described in [58]. $\Delta T_{in,out}$ is the difference between collector inlet or outlet temperature and ambient temperature and DNI is the direct normal irradiation.
The net thermal power delivered by the solar field is then calculated using

(3)
$$\dot{Q}_{net} = \dot{Q}_{abs} - \dot{Q}_{pipe}$$

with

(4)
$$\dot{Q}_{abs} = A_{eff} \cdot DNI \cdot \eta_{sf}$$

$\dot{Q}_{pipe}$ has a more complex formula, and accounts for losses in the piping and expansion vessel using empirical coefficients (i.e. tank heat loss rate at 275 °C [kW], piping heat loss/area at 343 °C [W/m²]). The model considers also electrical parasitics for tracking, start-up and shutdown as well as for pumping. The shutdown is performed automatically at high wind speeds (v>13 m/s).
A flow rate ramp-down period is now included so that the flow rate at the end of the day is linearly decreased to a level (RDRatio) normally higher than the turn-down ratio (TDR) over a specified time period (RDTime). The fraction of field tracking the sun can be specified by the user as a control input [57].

Biomass Unit

To simplify the modelization of the biomass unit, an "auxiliary heater" (type 6) is used to elevate the temperature of the thermal oil (HTF) from 293°C to a setpoint temperature (T_{set}) equal to 393°C. The heater is designed to add heat to the stream of oil at a rate less than or equal to $\dot{Q}_{max}$, which is assumed to be 44 MW_{th} as the gross power of the two biomass boilers. The thermal energy transfer to the stream of oil is expressed by the following equation,

(6) $$\dot{Q}_{bio} = \dot{m}_{htf} \cdot C_{p,htf} \cdot (T_{out} - T_{in}) \cdot \eta_{htr}$$

where $\dot{Q}_{max}$ is multiplied by η_{htr}, the efficiency of the biomass boilers, equal to 77% [48]. In the end, a net power of 34 MW_{th} is obtained for the biomass unit [58]. The implementation of the auxiliary heater is made in order to simplify the modelization of the biomass unit. However, the transfer of thermal energy to the thermal oil is carried out in such a way that the boiler fumes, generated by the biomass combustion, flow at a temperature of 900°C through the radiation chamber where the transfer of the energy takes place. The "furnace" (type 121) models this process, and the equation describing it is reported below to better understand it. The energy balance of the furnace is as follows [59],

(7) $$\dot{Q}_{furnace} = \dot{m}_{air} \cdot C_{p,air}\left(T_{air,out} - T_{air,in}\right) + UA \cdot (\bar{T} - T_{env})$$

and if equalized to (6), knowing the mass flow rate of HTF, gives the mass flow of air necessary to elevate the temperature of the thermal oil (HTF) from 293°C to the setpoint temperature (T_{set}) of 393°C. Before entering the biomass unit, this combustion air is preheated by the still hot fumes which circulate through a heat recovery system. However, as explained before the furnace (type 121) is not utilized since heat transfer phenomena are not analyzed in this work, and the auxiliary heater (type 6) is sufficient for the modelization of the heating process of the HTF from the biomass unit.

Power Block

The modelization of the interim heating *MARC-R* steam turbine is done through the "turbine stage" (type 318). This turbine stage model calculates the inlet pressure of the turbine stage from the outlet pressure, the steam mass flow rate and reference values of inlet and outlet pressure and mass flow rate using Stodola's law of the ellipse. It evaluates the outlet enthalpy from the inlet enthalpy and inlet and outlet pressure using an isentropic efficiency [59]. This is calculated, considering a reference value of 80%, by

(8) $$\eta_{is} = \eta_{is,ref} \cdot (1 + a \cdot f_{is} + b \cdot {f_{is}}^2 + c \cdot {f_{is}}^3) \qquad \text{limited between 0.2 and 1}$$

with

(9) $$f_{is} = \frac{\dot{m} - \dot{m}_{ref}}{\dot{m}_{ref}} \qquad \text{limited between } \pm 0.7$$

and

(10) $$h_{out} = h_{in} - \eta_{is} \cdot (h_{in} - h_{in,is})$$

The power generated by the turbine is in the end equal to

(11) $$P_{gen} = m_{in} \cdot \eta_{gen} \cdot (h_{in} - h_{out})$$

considering a generator efficiency of 98%. The turbine stage model is utilized two times since the reheating process of the steam after the first expansion has to be modeled.

Control System

For keeping the power plant in constant operation, it is crucial to assure a constant flow of thermal oil (HTF) to the heat recovery steam generator (HRSG), in order to generate steam and run the Rankine cycle. This is done through a specifically designed control system which balances the streams of HTF coming from the solar field and the biomass unit, in order to obtain a unique stream, at a given temperature and pressure, to feed the HRSG. Not existing any specific component for this purpose in the built-in *TRNSYS* library, the "equa" component is used, together with user-defined equations, in order to implement the control mechanism. The main principle behind it is that solar energy is intermittent, and must be exploited as much as possible giving priority to the flow of thermal oil coming from the solar field. The biomass unit is used as a support, during the daytime, and an alternative, during the night time, for heating the remaining part of the required mass flow rate of thermal oil. Considering the rated power of the solar field and biomass unit, the maximum mass flow rates of thermal oil coming from them are respectively equal to

(12) $$\dot{M}_{htf,sf,max} = \frac{\dot{Q}_{net,max}}{c_{p,htf} \cdot (T_{out} - T_{in})} = \frac{68000}{2.303 \cdot (393 - 293)} \cong 296 \text{ kg/s}$$

and

(13) $$\dot{M}_{htf,bio,max} = \frac{\dot{Q}_{bu,max}}{c_{p,htf} \cdot (T_{out} - T_{in})} = \frac{34000}{2.303 \cdot (393 - 293)} \cong 147 \text{ kg/s}$$

the control of the mass flow rate of thermal oil required from the biomass unit is done through the following equations

$$
\begin{cases}
(14)\ \dot{M}_{htf,bio} = \dot{M}_{htf,bio,max}\,, & \text{if } \dot{M}_{htf,sf,max} - \dot{M}_{htf,sf} > \dot{M}_{htf,bio,max} \\
(15)\ \dot{M}_{htf,bio} = \dot{M}_{htf,sf,max} - \dot{M}_{htf,sf}\,, & \text{if } \dot{M}_{htf,sf,max} - \dot{M}_{htf,sf} < \dot{M}_{htf,bio,max}
\end{cases}
$$

In this way, we assure that every moment during daytime in which the mass flow rate coming from the solar field is not enough to run the steam cycle alone, the biomass unit is turned on to support the generation of the required mass flow rate of thermal oil. The maximum thermal power which can be delivered by the biomass unit is 34 MW. This is the reason why the control of $\dot{M}_{htf,bio}$ is made in relation to the maximum mass flow rate of thermal oil which the biomass unit is capable of generating, $\dot{M}_{htf,bio,max}$, instead of $\dot{M}_{htf,sf,max}$. Otherwise, values of required mass flow rate from the biomass unit above its generating capability would be obtained. This control system also automatically adjusts itself in case no solar radiation is available, or during night time. In fact, in both cases the maximum mass flow rate of thermal oil fed to the HRSG corresponds to the one of the biomass unit alone (i.e. 147 kg/s), leading to a gross power generation of 12.5 MW_e, half of the nominal power generation during daytime, as in the reference power plant [48].

2.2.3. *TRNSYS* Simulation

The purpose of using *TRNSYS* software for the modeling and simulation of the power plant is to study its operation at weather conditions different from the reference values. At this off design weather conditions, the power plant generates less power than the rated capacity, and the software automatically adjusts the working points for the steam turbines giving the effective hourly power generation. This becomes really useful when calculating the yearly performance of a power plant based mainly on the solar resource, because of the variability of solar radiation due to transients (e.g. clouds). The main components used, all taken from *TRNSYS* standard library and STEC library, are Types 16a and 54a as weather data processors, Types 397 and 6 for the parabolic trough solar field and biomass unit, Types 11f and 11h as HTF splitter and mixer, Types 315 and 316 for the heat recovery steam generator, respectively for the economizer/superheater/reheater and evaporator, and Types 318 and 383 for the turbine stages and condenser. Since some extractions are performed at the different turbine stages, Types 331 and 317 are used respectively as steam/vapor splitter and water preheaters. Finally, Types 300 and 390 are used as pumps for the HTF and condensates. *TRNSYS* model is used to estimate the input and output temperatures of HTF and steam for all the components at different operating conditions. Similarly, the mass flow rates of HTF and steam, the heat transferred between them and the net power output from the plant are determined. An overview of the simulation window is presented in the following Figure 2.9, while in Figure 2.10 is shown the power plant scheme, in which all the components with their relative connections can be distinguished.

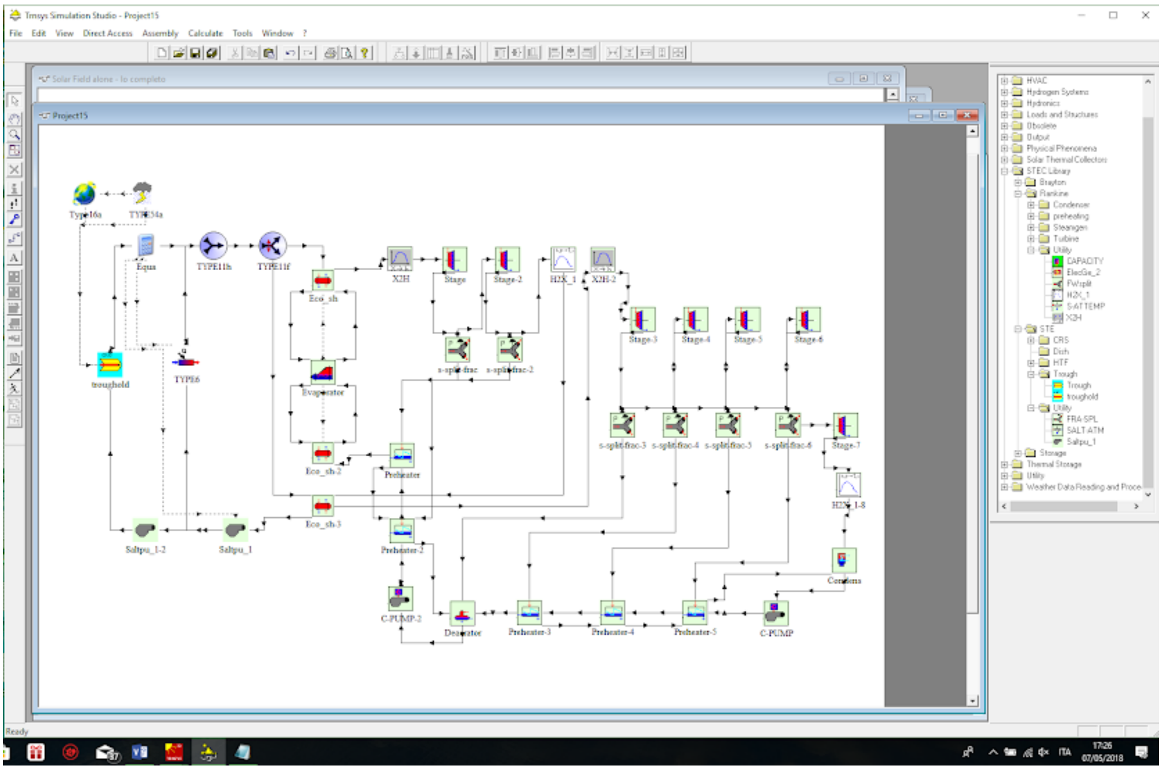

Figure 2.9: TRNSYS software: main simulation window

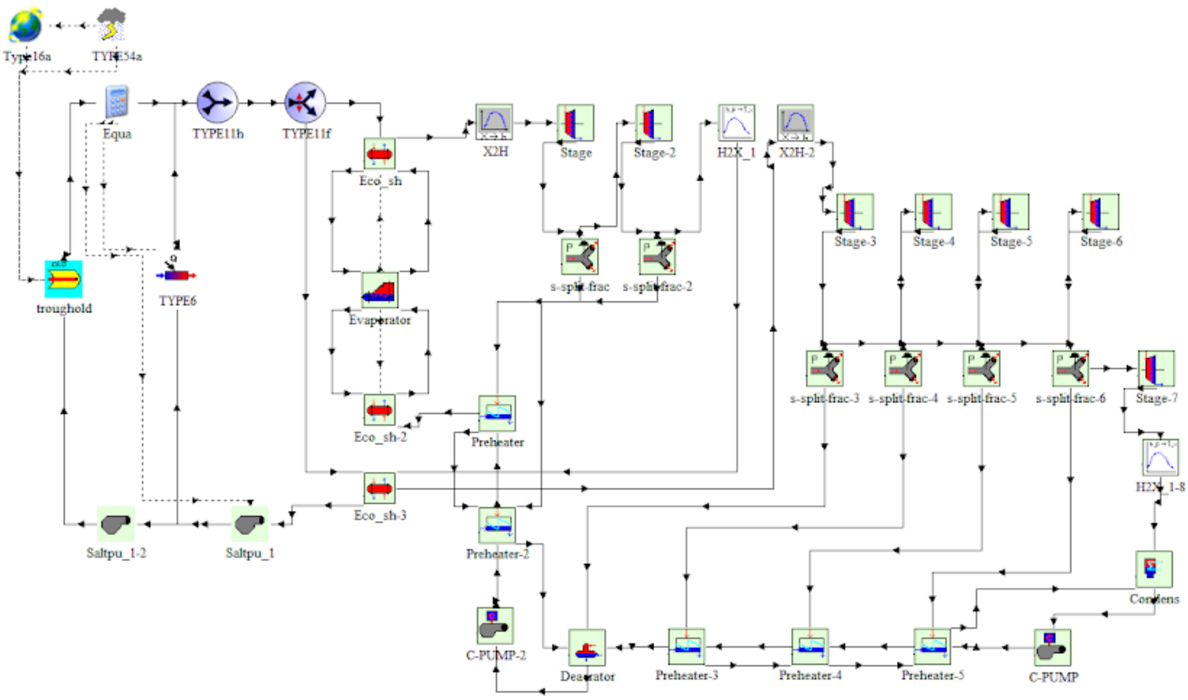

Figure 2.10: TRNSYS software: model of the Termosolar Borges power plant with all the components and relative connections

2.3. Simulation Results

2.3.1. Annual Results

The annual results obtained from the simulation of the power plant are shown in Table 2.6. The two columns of the table show respectively the simulated results and the expected ones, in order to perform a comparison with the reference plant and check if the model utilized was consistent and the simulation was performed correctly. The simulated yearly electricity generation is 98800 MWh, very

Table 2.6: Simulated and expected annual results of the 25 MW_e Termosolar Borges power plant

	Simulated	Expected
DNI [kWh/m² year]	1782	1800
Net Electricity Generation [MWh_e/year]	98800	98000
Electrical Efficiency [%]	36-37	33-37
Capacity Factor [%]	50.1	49.7
Eq. Hours of Operation [Hours/year]	6442	6354
Biomass Consumption [Tonnes/year]	62160	70000
Biomass Energy [MWh_{th}/year]	186481	210000

close to the 98000 MWh of the real power plant, with a slightly higher power cycle efficiency in the simulated case, around 36%, especially during night operation (33% for the real case). This is divided into 34175 MWh from the solar field (34.6%) and 55385 MWh from the biomass unit (54.1%), with the remaining part of 9180 MWh (9.3%) generated from the additional natural gas boilers. The capacity factor of 50.1% is slightly higher than the real one (49.7%), and the same occurs for the hours of operation, 6442 hours against 6354 hours. In particular, the operating hours of the solar field throughout the year account for 1519 hours, with a corresponding capacity factor of 17.3%. For the biomass unit, the operating hours are 4923 hours, leading to a capacity factor of 56.2%. In contrast to the real power plant, the solar field is operating around 500 hours more than in the real power plant, and the same amount of hours represents the difference between the simulated and expected operating hours of the biomass unit. Due to the correlation between the two outputs, it can be deduced that the meteorological file could play a role in this discrepancy, leading to a better performance of the solar field to the detriment of the biomass unit. The same conclusion explains the difference in the simulated and expected biomass energy and biomass consumptions: 170940 MWh corresponding to 56980 tonnes in the simulated case, against the 210000 MWh and 70000 tonnes of the real power plant. Having obtained the same electrical efficiency (around 36%) as in the real case, and assumed the same LHV of the biomass feedstock (3 kWh/kg), the deviation only depends on the reduced generation of the biomass unit of the simulated plant, with the consequent reduced consumption of biomass feedstock. The annual simulation results are also presented on a monthly basis in Table 2.7 below.

Table 2.7: Estimated monthly gross electricity generation (in kWh) based on CSP, biomass combustion and natural gas for the 25 MW_e Termosolar Borges power plant

	CSP	Biomass	Natural Gas	Total
January	31436	9268880	0	9300316
February	246662	8596413	0	8843075
March	1277573	8290414	0	9567987
April	3655767	7050593	0	10706359
May	7156146	5673526	0	12829672
June	8778120	4543677	0	13321796
July	8918858	0	3400000	12318858
August	5562749	0	3400000	8962749
September	1987769	0	3400000	5387769
October	343689	9137027	0	9480716
November	13536	8978214	0	8991750
December	0	0	0	0
ANNUAL	37972304	61538743	10200000	109711047

As it can be noticed, the power generation in December is equal to zero, being the operation of the power plant suspended for maintenance issues. The overall electricity output is relatively stable throughout the year between 8800-9500 MWh, with peaks in summer of about 13000 MWh, and lowest generation in September of about 5300 MWh. This is due to the fact that the operational period is divided in 8 months on hybridization mode, during winter time, and 3 months on solar mode, corresponding to the July-September period, to not exceed the quota for biomass burning that establishes the regulations (i.e. 50% electricity generation from biomass) [48]. In this way, the power plant benefits from the relatively high contribution from the solar field in summer, still operating the biomass unit. On the other hand, during the shut down period for the biomass unit, the additional natural gas boilers are used to support the solar field for heating the HTF, leading to a reduction in the electricity generation which reaches the minimum in September, when the solar field contributes in a little extent due to the reduced solar DNI.

The monthly contribution of the three different resources to the total electricity generation can be seen in Figure 2.11. The maximum contribution from the solar field is reached during the summer period (72.4%), when the biomass unit is stopped, with a CSP electricity generation of 8918 MWh. In contrast, the biomass reaches over 98% of contribution during the winter months when solar DNI is very low and the power plant relies almost entirely on the biomass resource, leading to an electricity generation of 8978 MWh in November and 9268 MWh in January. The supplemental natural gas boilers are operated only during the biomass unit shut down period, resulting in contributions of 27.6%, 37.9% and 63.1% respectively in July, August and September. The simulation results are also presented on a daily basis in the following sections, for some typical days of operation (e.g. sunny/cloudy day).

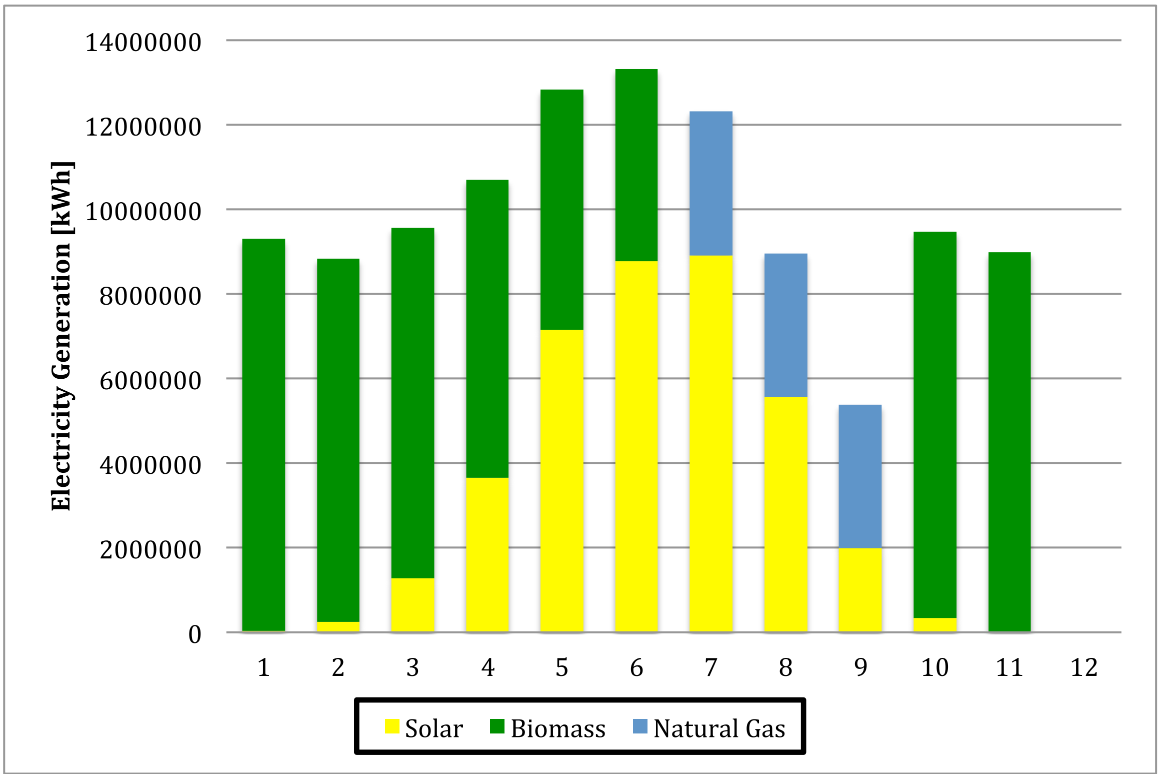

Figure 2.11: Estimated monthly contribution based on CSP, biomass combustion and natural gas to the total electricity generation for the 25 MW_e Termosolar Borges power plant

2.3.2. Sunny Day

The simulation results are showed on a daily basis in the following Figures 2.12-2.19, for the 15th of June and the 19th of March, respectively representatives of a clear day and a cloudy day. On a clear day such as June 15th, the power plant operates at its maximum capacity for a period of about 10 hours (8:00 – 17:00 hours, Figure 2.13), while the rest of the day including night, when the DNI is lower than the minimum required for operating the solar field (Fig. 2.12), it operates at half of its rated power thanks to the support of the biomass unit. The mass flow rate of the HTF flowing in the HRSG, and the steam running the Rankine cycle, are shown respectively in Figures 2.14 and 2.15. In both Figures, the mass flow rates of HTF and steam relative to the two components (i.e. solar field and biomass unit) were showed, in order to appreciate the contribution of the two to the total mass flow rates of HTF, and the equivalent amount of steam generated. Similar results are shown for a cloudy day, March 19th, in Figures 2.16-2.19. The main difference is that the power plant operates at a lower capacity than its maximum, with the aid of the biomass unit which operates as support to the solar field when solar radiation is not available, with increased electricity generation compared to a clear day (Fig. 2.17). As a consequence, the amount of HTF coming from the biomass unit is increased (Fig. 2.18), especially during transient periods, and so more steam is generated thanks to it (Fig. 2.19). It is particularly interesting to see how the biomass unit helps the power plant keeping the gross electricity generation always equal or above 12.5 MW_e, being a great advantage for the power block, determining improved operating conditions for the plant.

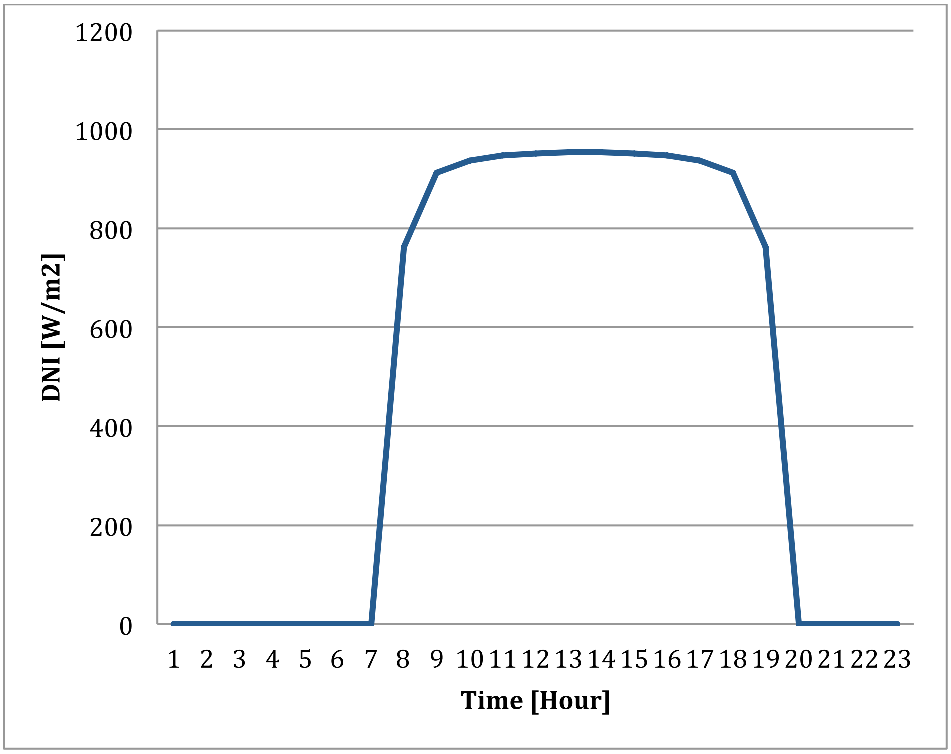

Figure 2.12: Direct Normal Irradiation (DNI) on a clear day

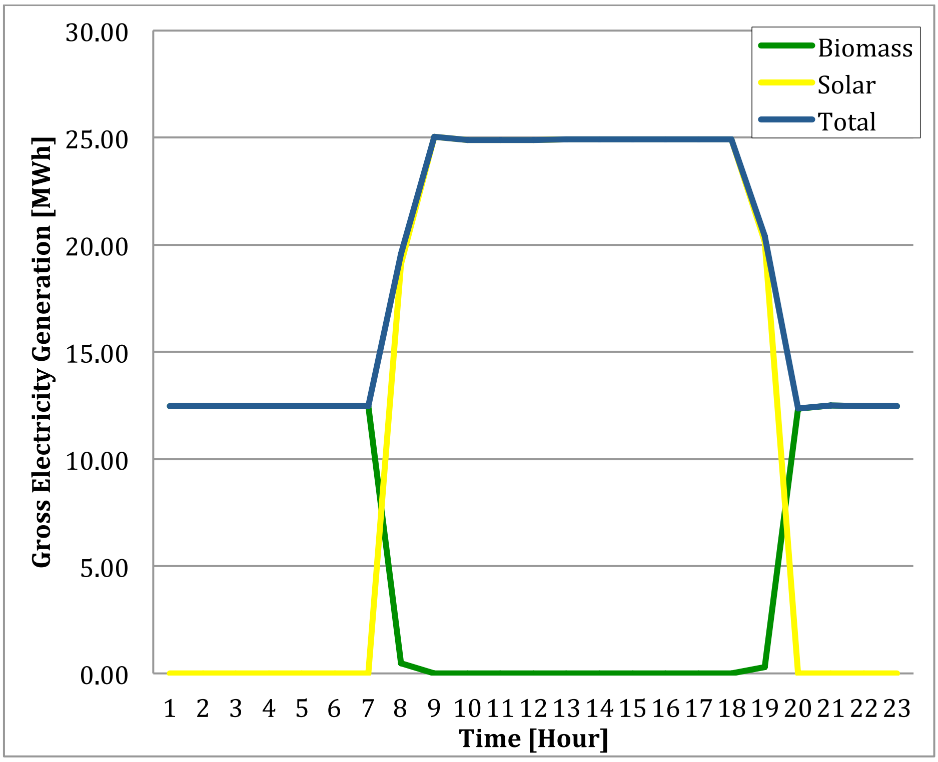

Figure 2.13: Gross electricity generation on a clear day

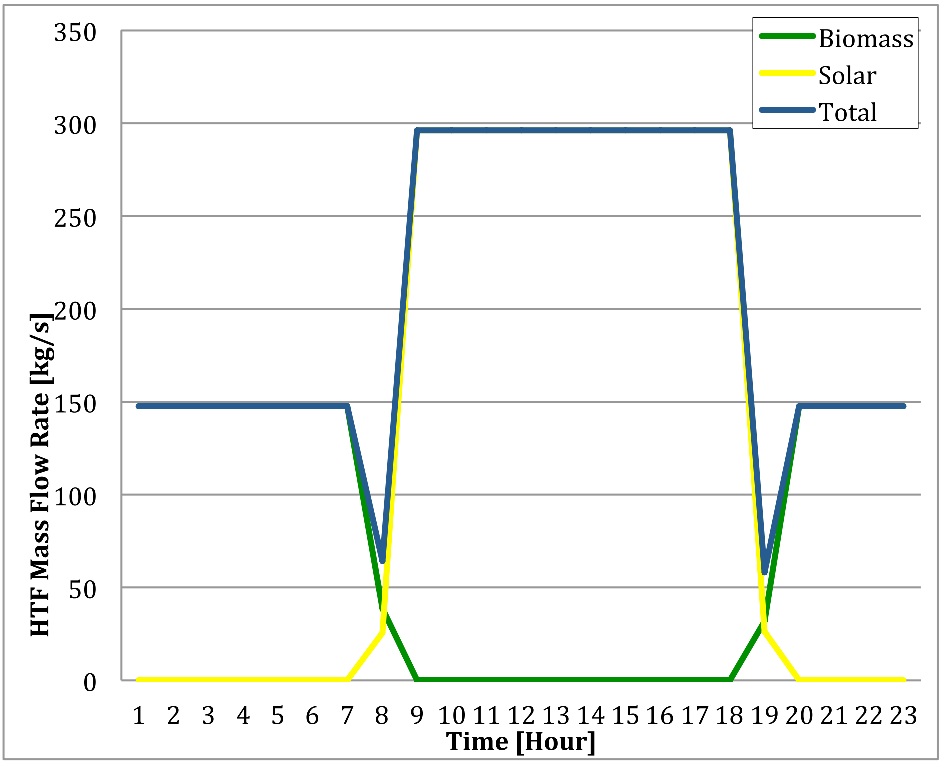

Figure 2.14: HTF mass flow rate on a clear day

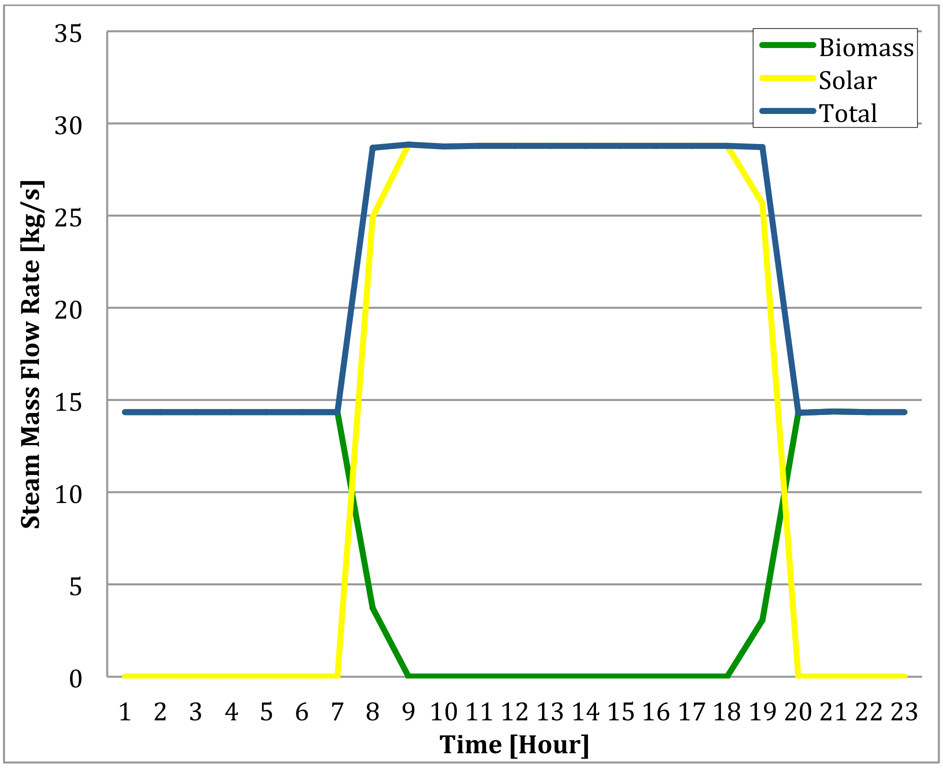

Figure 2.15: Steam mass flow rate on a clear day

2.3.3. Cloudy Day

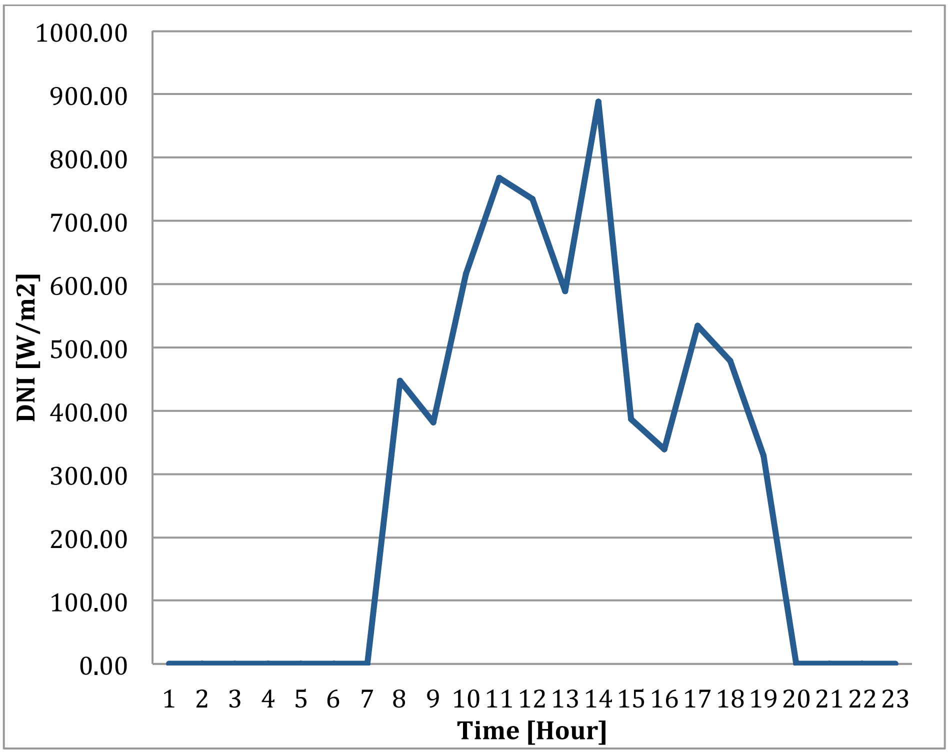

Figure 2.16: Direct Normal Irradiation (DNI) on a cloudy day

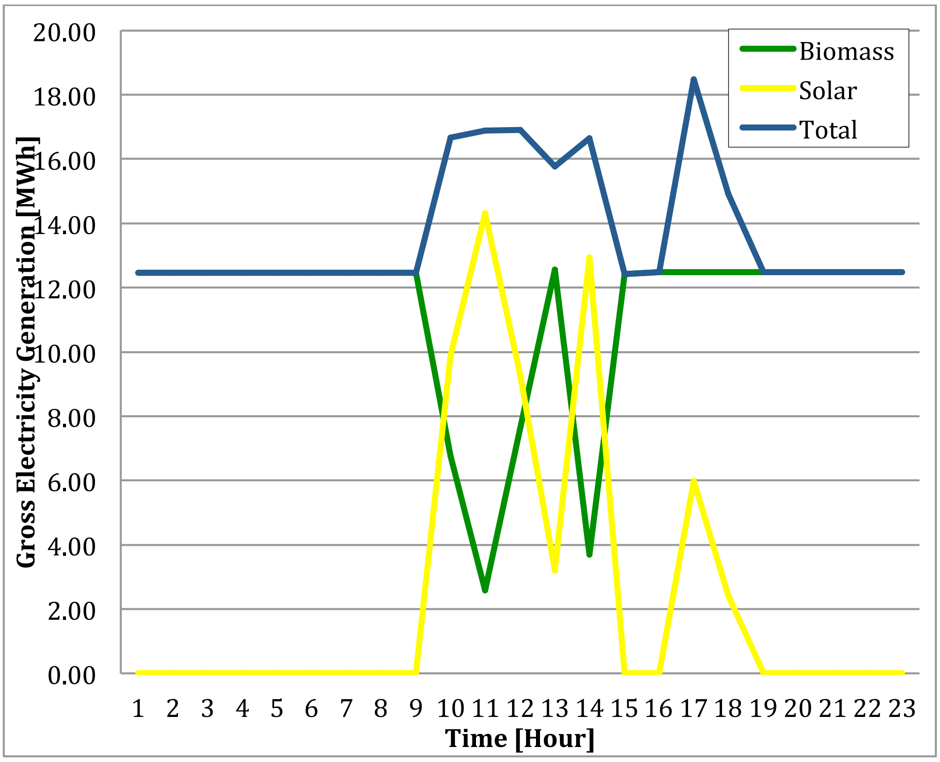

Figure 2.17: Gross electricity generation on a cloudy day

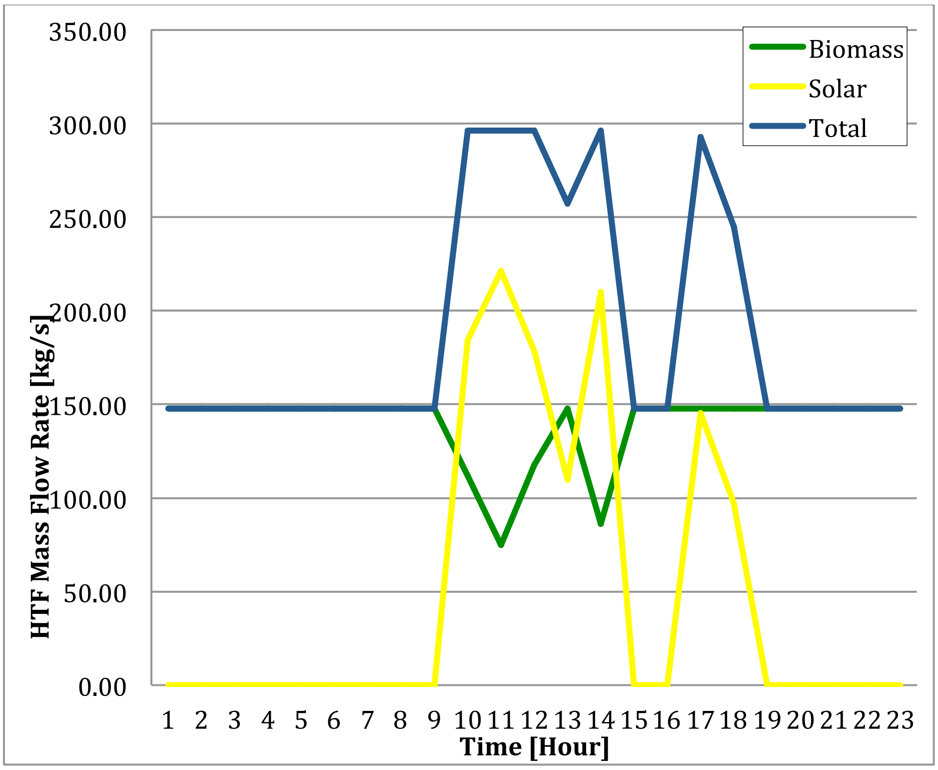

Figure 2.18: HTF mass flow rate on a cloudy day

ETSEIB

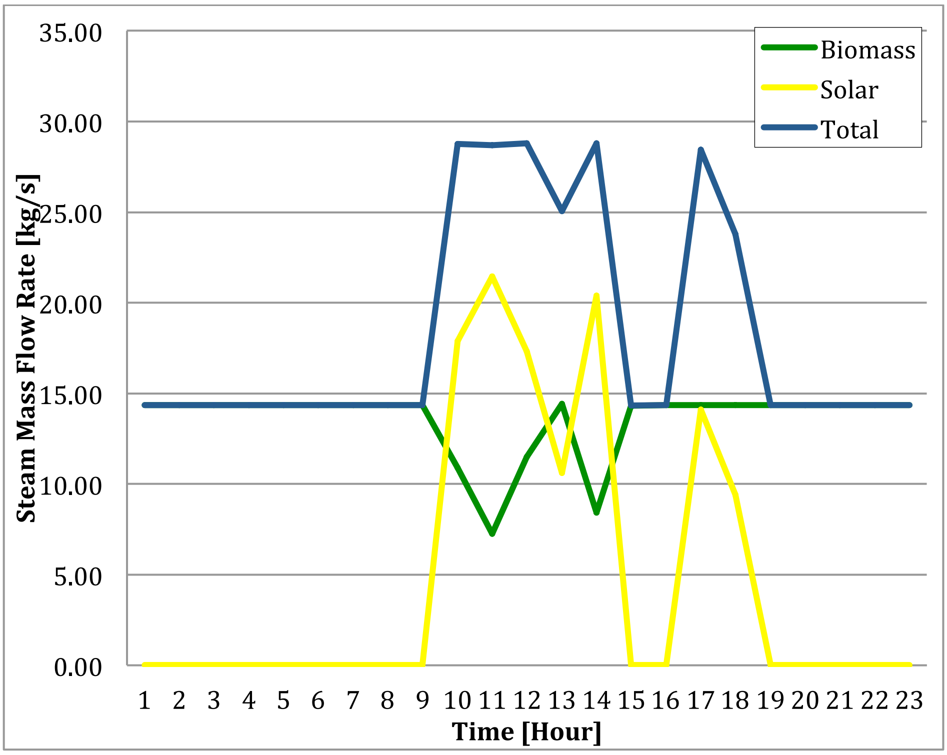

Figure 2.19: Steam mass flow rate on a cloudy day

2.4. Cost Analysis

Besides the annual operational results, some economic parameters are also calculated in order to make more complete the analysis of the simulated power plant. The first parameter to be analyzed is the total investment cost, which has been calculated for a 25 MW_e CSP-biomass hybrid power plant, with a solar field aperture area of 183120 m^2, as well as for two independents power plants based respectively on CSP and biomass combustion technologies having the same characteristics as the previous one, in order to assess the cost of implementing only one of the two technologies alone. The breakdown of the specific investment costs for the three cases is shown in Table 2.8 below.

Table 2.8: Specific investment costs for three power plant based on CSP, biomass combustion and hybrid CSP-biomass technologies

CSP plant			Biomass Combustion plant			Hybrid CSP-biomass plant		
			Biomass Treatment Plant	600	€/kW	Biomass Treatment Plant	600	€/kW
			Biomass Boiler	1200	€/kW	Biomass Boiler	1120	€/kW
Solar Field	1831	€/kW				Solar Field	1831	€/kW
Heat Recovery Boiler	400	€/kW				Heat Recovery Boiler	400	€/kW
Heat Transfer System	586	€/kW				Heat Transfer System	879	€/kW
Turbogenerator Set	400	€/kW	Turbogenerator Set	400	€/kW	Turbogenerator Set	400	€/kW
BOP	120	€/kW	BOP	120	€/kW	BOP	120	€/kW
Civil Works	366	€/kW	Civil Works	366	€/kW	Civil Works	366	€/kW
Total Specific Cost	4597	€/kW	Total Specific Cost	3334	€/kW	Total Specific Cost	6077	€/kW
Total Investment	115	M€	Total Investment	41.7	M€	Total Investment	152	M€

For the CSP power plant, a gross installed capacity of 25 MW_e was considered, while for the Biomass power plant it was set to 12.5 MW_e, as the installed capacity of the biomass unit of the Termosolar Borges. The results show that the investment cost per unit of installed capacity for a hybrid CSP-biomass power plant is 6077 €/kW. This cost is higher than in the cases of CSP or Biomass combustion technologies, which have a specific investment cost of respectively 4597 €/kW and 3334 €/kW. The total investment costs resulted equal to about 152, 41.7 and 115 million € respectively for the three power plants based on Hybrid, Biomass combustion and CSP technologies. In the end, the total investment cost for the hybrid solution is very close to the Termosolas Borges power plant, which had an investment of 153 million €. It is calculated that even if the specific investment cost for the hybrid power plant is higher than in the other two cases, there is a 23% saving compared to the simple addition of the two standard technologies. This is due to the fact that some components are shared during the operation of the hybrid power plant, leading to a net saving in the investment costs thanks to the already discussed synergies of the two standard technologies.

Regarding the second economic parameter that is analyzed, this is the levelized cost of electricity (LCOE). The value of the LCOE for the three cases is shown in Table 2.9 together with some performance parameters. As it can be noted, it may be concluded that the biomass combustion power plant provides the cheapest alternative, with an LCOE of 75.7 €/MWh, so it represents the most convenient alternative. However, this solution relies on the supply of a large amount of biomass feedstock, estimated around 73333 tonnes/year, which, even if does not exceed the quantity available

Table 2.9: Comparative economic and performance assessment for three power plants based on CSP, biomass combustion and hybrid CSP-biomass technologies

	CSP plant	**Biomass Combustion plant**	**Hybrid CSP-biomass plant**
Total Investment [€]	115000000	41700000	152000000
Operating Costs [€/year]	777066	4476860	3942701
Eq. Hours of Operation [Hours/year]	1519	8016	6442
Biomass Consumption [Tonnes/year]	0	73333	62160
Net Electricity Generation [MWh/year]	34175	100200	98800
LCOE [€/MWh]	273.6	75.7	150.9

locally in the region, around 60000-90000 tonnes/year [60], still represents a challenge for the supply chain, keeping into account that also the highly volatile price of it can represent a constraint during operation. Considering the hybrid CSP-biomass power plant, it is calculated an LCOE of 150.9 €/MWh which is almost twice the one of the biomass combustion plant, but 56% lower than the conventional CSP plant. The biomass feedstock requirement is reduced, estimated around 62160 tonnes/year, while the electricity generation is very close to the biomass combustion plant alternative. It can be concluded that despite the higher investment cost, 32% higher than the CSP plant, the hybrid solution represents the great advantages of relying on a sustainable supply of biomass feedstock, having a sensibly increased electricity generation, so representing a better and cheaper alternative with respect to the CSP plant, with a better performance considering the increased hours of operation (4.24 times higher) and electricity generation (2.89 times higher) and a much lower LCOE.

3. Upscaling and Simulation of the 50 MWe Hybrid Power Plant

In the previous section, it was presented a comprehensive analysis of the only existing CSP-biomass power plant in the World, the *Termosolar Borges* operating in Lleida, Spain. After an extensive description of the plant, a numerical simulation through *TRNSYS* software was conducted in order to reproduce the operating conditions of the plant and simulate its outputs. In the end, the simulation results allowed to validate the model and prove its consistency, even if minor deviations from the real operating parameters of the plant were found. In this section, the focus is put on the upscaling of the simulated power plant to a gross capacity of 50 MW_e, simulation and analysis of the same plant using the same methodology as in the previous section, to obtain the annual performance parameters of a hybrid power plant twice the size of the *Termosolar Borges*, but the same size of a typical CSP power plant in Spain. Finally, a technical and economical comparison is conducted, between the reference 25 MW and upscaled 50 MW power plants with conventional 50 MW_e CSP power plants in Spain and in the World, with and without TES, in order to check if the hybrid CSP-biomass configuration can be competitive from the point of view of the performance, and economics, with conventional power plants. (Biomass combustion power plants are also included in this final study, being biomass one of the two sources of primary energy, together with solar radiation, on which the hybrid power plant rely.)

3.1 Upscaling of the Reference Power Plant

After having properly simulated the reference power plant, and checked the consistency of the model developed, it is possible to upscale it to the size of conventional CSP power plants operating in Spain, around 50 MW_e of gross capacity, taking into account all the advantages of increasing the installed capacity of a power plant (e.g. increased electricity generation, reduced LCOE). In order to do so, the size and capacities of the main components of the reference power plant are upscaled to double their values, to obtain in the end double the rated capacity of the *Termosolar Borges* power plant. The process of upscaling and consequent analysis of the new plant follow the same methodology adopted during the simulation of the reference power plant. This means that all the assumptions made regarding the power cycle and operating parameters, the mathematical models of the components as well as their inputs are kept the same as in the base case. The main difference is represented by the new technical characteristics of the solar field and biomass unit, which are now upscaled in order to obtain double the thermal power required to run the Rankine cycle at double the rated capacity. The aperture area of the solar field is increased from 183120 m^2 to 366240 m^2, while the net thermal capacity of the biomass unit is increased from 34 MW_{th} to 68 MW_{th}, with a grate-firing capacity that reach 88 MW_{th}. Regarding the power block, the design flow rate of the HP and LP stages of the steam turbines are maintained the same, so that doubling the steam mass flow rate, the gross capacity of the Rankine cycle is upscaled to 50 MW_e. The characteristics of all the other components, including the HRSG (economizer, evaporator, superheater and reheater) and condenser are kept the same. To better understand the changes made to the power plant components, their new technical parameters are showed in Table 2.2.

Table 3.1: Technical parameters of the main components of the upscaled 50 MW_e hybrid power plant

Parabolic Trough		**Biomass Unit (2 x Biomass Boilers)**	
Length of SCA	96 m	Grate Firing Capacity	4 x 22 MW_{th}
Aperture Width of SCA	5.77 m	Boilers Efficiency	77%
Focal Lenght of SCA	2.17 m	Biomass Feedstock LHV	3.05 kWh/kg
Row Spacing	15 m	Inlet Temperature Biomass Unit	293°C
Total Field Area	366240 m^2	**Super Heater/Reheater**	
Inlet Temperature Solar Field	293 °C	Source Side Inlet Temperature	393°C
Cleanliness Solar Field	0.95	Superheater Source Side Flow Rate	1833670
Specific Heat HTF	2.303 kJ/kgK	Superheater Load Side Inlet	kg/hr
Density HTF	900 kg/m^3	Temperatur	311°C
Wind Speed Limit for Tracking	13.5 m/s	Reheater Source Side Flow Rate	298505 kg/hr
		Reheater Load Side Inlet	223 °C
		Temperature	
Preheater		**Evaporator**	
Source Side Inlet Temperature	311°C	Source Side Inlet Temperature	376°C
Load Side Inlet Temperature	250°C	Load Side Inlet Temperature	311°C
Load Side Flow Rate	214690 kg/hr	Load Side Outlet Pressure	100 bar
Turbine		**Condenser**	
Turbine Outlet Pressure (HP	25 bar	Cooling Water Inlet Temperature	28°C
stage)	0.060 bar	Cooling Water Mass Flow Rate	22228.2
Turbine Outlet Pressure (LP	214690 kg/hr	Temperature Increase Cooling	ton/hr 3 °C
stage)	183670 kg/hr	Water	2368.5 kJ/kg
Turbine Inlet Flow Rate (HP	3018.7 kJ/kg	Inlet Steam Enthalpy	139838 kg/hr
stage) Turbine Inlet Flow Rate	3187.5 kJ/kg	Steam Mass Flow Rate	36 °C
(HP stage)	80%	Condensing Temperature	0.060 bar
Turbine Inlet Enthalpy (HP		Condensing Pressure	
stage)			
Turbine Inlet Enthalpy (LP stage)			
Design Inner Efficiency			

3.2 Simulation Results

3.2.1. Annual Results

The annual results obtained from the simulation of the upscaled 50 MW_e hybrid power plant are shown in Table 3.2, together with the results obtained from the previous simulation of the Termosolar Borges power plant. The power cycle efficiency is the same as the simulated 25 MW_e plant, around 36%, being the model utilized the same as in the previous simulation. This leads to a yearly electricity generation of the upscaled plant of 197118 MWh, almost twice the generation of the real power plant, divided into 68711 MWh from the solar field (34.9%) and 110047 MWh from the biomass unit (55.8%), with the remaining part of 18360 MWh (9.3%) generated from the additional natural gas boilers. The shares are very close to the ones obtained in the previous simulation, as well as the capacity factor of 50% very close to the 50.1%. Regarding the hours of operation, for the upscaled plant, 6418 hours are obtained against the 6442 hours of the 25 MW_e plant. In particular, the operating hours of the solar field throughout the year account for 1527 against the previous 1519 hours, with a corresponding slightly higher capacity factor of 17.4%, while for the biomass unit the operating hours are 4891 against the previous 4923 hours, leading to a lower capacity factor of 55.8%.

Table 3.2: Simulated annual results of the upscaled 50 MW_e hybrid power plant compared to the 25 MW_e Termosolar Borges power plant

	Simulated	**Termosolar Borges (sim.)**
DNI [kWh/m^2 year]	1782	1782
Net Electricity Generation [MWh_e/year]	197118	98800
Electrical Efficiency [%]	36-37	36-37
Capacity Factor [%]	50.0	50.1
Eq. Hours of Operation [Hours/year]	6418	6442
Biomass Consumption [Tonnes/year]	123510	62160
Biomass Energy [MWh_{th}/year]	370528	186481

Regarding the biomass consumption, it is much higher in the upscaled power plant accounting for 123510 tonnes relative to 370528 MWh of biomass energy, against the 62160 tonnes of the 25 MW_e plant. As it will be further discussed in the following chapters, this upscaled hybrid power plant relies on the supply of a very large amount of biomass feedstock, which exceeds the quantity available locally in the region, around 60000 tonnes/year [60], representing a big constraint to its operation.

In the end, even if the annual electricity generation is twice the previous one, in the upscaled power plant the solar field is performing better, leading to a lower electricity generation from the biomass unit. This can be explained taking into account that for the design point of the solar field, a day of April was taken as reference day. So, when doubling the size of the solar field, this performs better in the winter months, compared to the summer months in which it was already performing at its maximum capacity in the previous 25 MW_e hybrid power plant simulation. This aspect can be appreciated even more when taking a look at the annual simulation results presented on a monthly basis in Table 3.3 below. The electricity generation in September, November, January and February is respectively 2.47, 2.55, 2.26 and 2.20 times higher than in the corresponding months in the 25 MW_e plant simulation, confirming what previously explained. In general, the power generation in December is equal to zero, being the operation of the power plant suspended for maintenance issues. The overall electricity output is relatively stable throughout the year between 17600-19000 MWh, with peaks in summer of about 26000 MWh, and lowest generation in September of about 11700 MWh. As already explained in the previous section, this is due to the fact that the operational period is divided in 8 months on hybridization mode, during winter time, and 3 months on solar mode, corresponding to the July-September period, to not exceed the quota for biomass burning that establishes the regulations (i.e. 50% electricity generation from biomass) [48].

Table 3.3: Estimated monthly gross electricity generation (in kWh) based on CSP, biomass combustion and natural gas for the upscaled 50 MW_e hybrid power plant

	CSP	Biomass	Natural Gas	Total
January	71049	18435675	0	18506723
February	543476	17082337	0	17625813
March	2710541	16455555	0	19166095
April	7482951	13990468	0	21473419
May	14250325	11261740	0	25512066
June	17399737	9032738	0	26432475
July	17709308	0	6800000	24509308
August	10481955	0	6800000	17281955
September	4914805	0	6800000	11714805
October	747700	18157724	0	18905424
November	34578	17858211	0	17892788
December	0	0	0	0
ANNUAL	76346423	122274447	20400000	219020871

In this way, the power plant benefits from the relatively high contribution from the solar field in summer, still operating the biomass unit. On the other hand, during the shut down period for the biomass unit, the additional natural gas boilers are used to support the solar field for heating the HTF, leading to a reduction in the electricity generation which reaches the minimum in September, when the solar field contributes in a little extent due to the reduced solar DNI.

The monthly contribution of the three different resources to the total electricity generation can be seen in Figure 2.11. The maximum contribution from the solar field is reached during the summer period (72.2%), when the biomass unit is stopped, with a CSP electricity generation of 17709 MWh. In contrast, the biomass reaches over 98% of contribution during the winter months when solar DNI is very low and the power plant relies almost entirely on the biomass resource, leading to an electricity generation of 17858 MWh in November and 18435 MWh in January. The supplemental natural gas boilers are operated only during the biomass unit shut down period, resulting in contributions of 27.7%, 39.3% and 58% respectively in July, August and September. The simulation results are also presented on a daily basis in the following sections, for some typical days of operation (e.g. sunny/cloudy day).

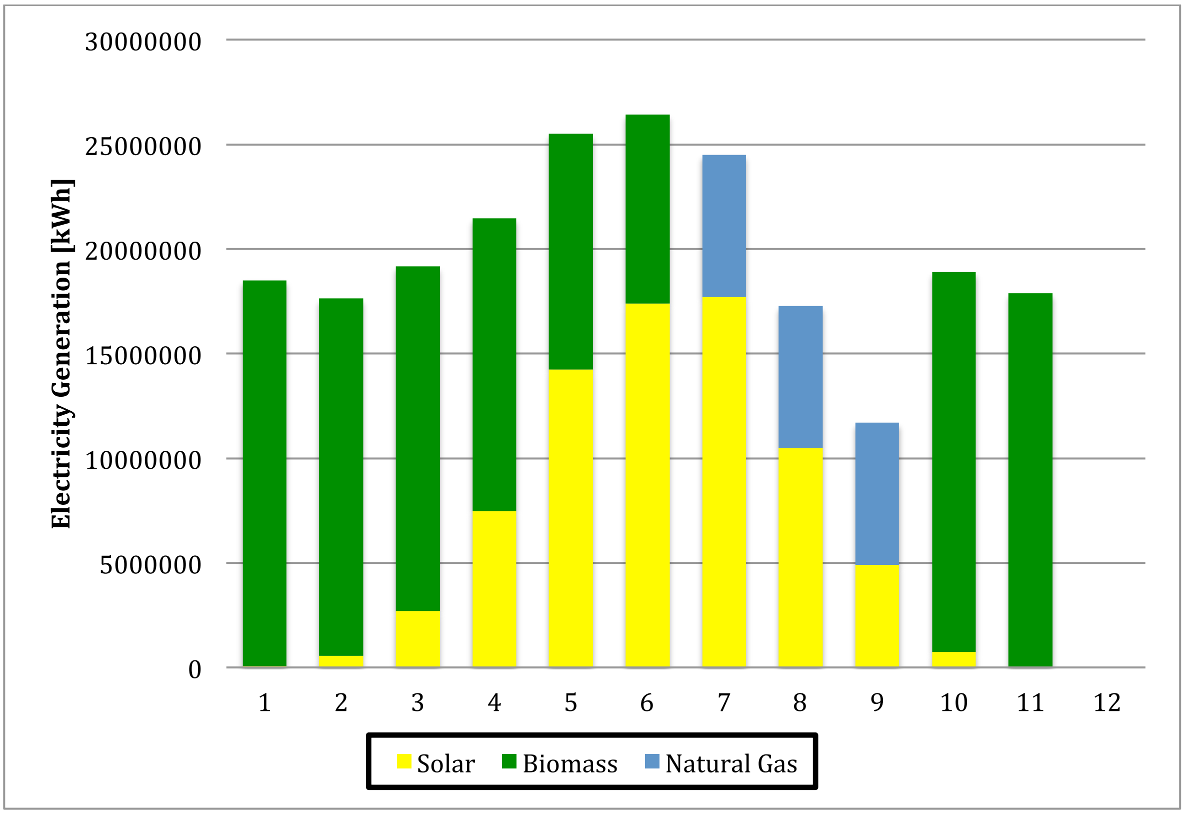

Figure 3.1: Estimated monthly contribution based on CSP, biomass combustion and natural gas to the total electricity generation for the upscaled 50 MW_e hybrid power plant

3.2.2. Sunny Day

The simulation results are shown on a daily basis in the following Figures 3.2-3.9, for the 15th of June and the 19th of March, respectively representatives of a clear day and a cloudy day. It can be noted that the daily performance of the upscaled power plant is the same from a qualitative point of view, while the mass flow rates of HTF and steam, as well as the electricity generation, are doubled in values. On a clear day such as June 15th, the power plant operates at its maximum capacity for a period of about 10 hours (8:00 – 17:00 hours, Figure 3.3), while the rest of the day including night, when the DNI is lower than the minimum required for operating the solar field (Fig. 3.2), it operates at half of its rated power thanks to the support of the biomass unit. The mass flow rate of the HTF flowing in the HRSG, and the steam running the Rankine cycle, are shown respectively in Figures 3.4 and 3.5. In both Figures, the mass flow rates of HTF and steam relative to the two components (i.e. solar field and biomass unit) were shown, in order to appreciate the contribution of the two to the total mass flow rates of HTF, and the equivalent amount of steam generated. Similar results are shown for a cloudy day, March 19th, in Figures 3.6-3.9. The main difference is that the power plant operates at a lower capacity than its maximum, with the aid of the biomass unit which operates as support to the solar field when solar radiation is not available, with increased electricity generation compared to a clear day (Fig. 3.7). As a consequence, the amount of HTF coming from the biomass unit is increased (Fig. 3.8), especially during transient periods, and so more steam is generated thanks to it (Fig. 3.9). It is particularly interesting to see how the biomass unit helps the power plant keeping the gross electricity generation always equal or above 25 MW_e, a great advantage for the power block determining improved operating conditions for the plant.

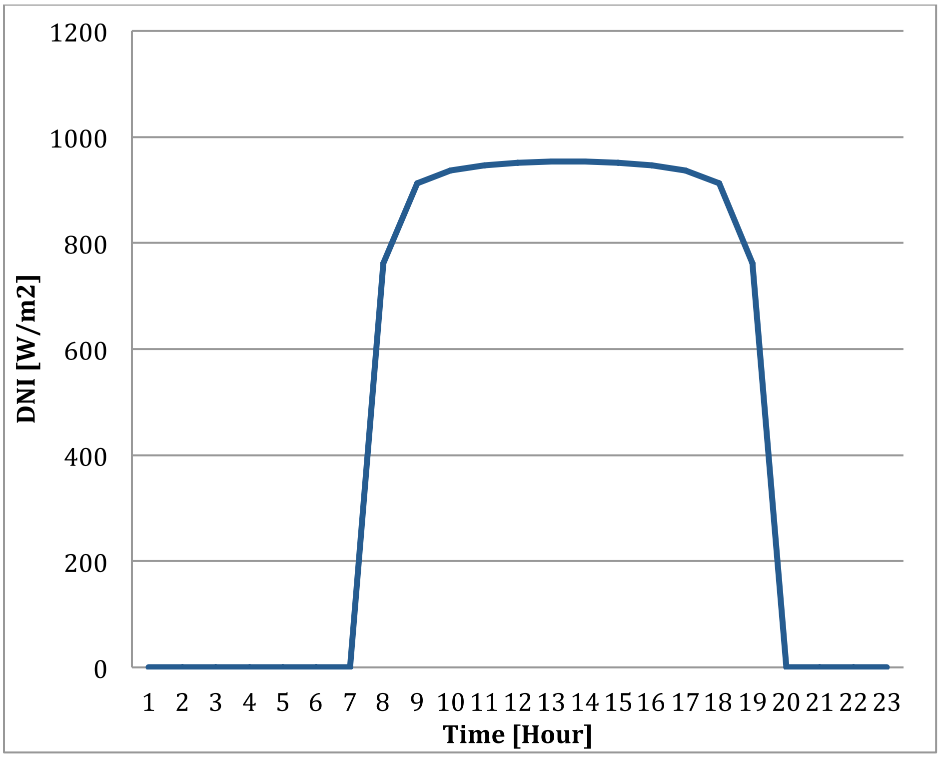

Figure 3.2: Direct Normal Irradiation (DNI) on a clear day

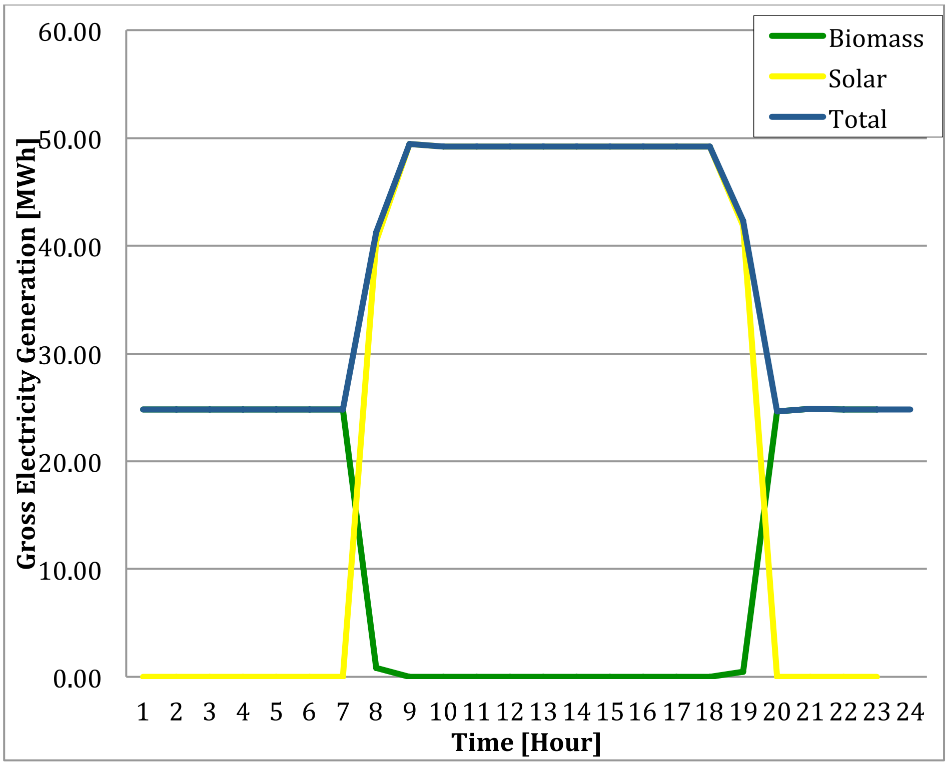

Figure 3.3: Gross electricity generation on a clear day

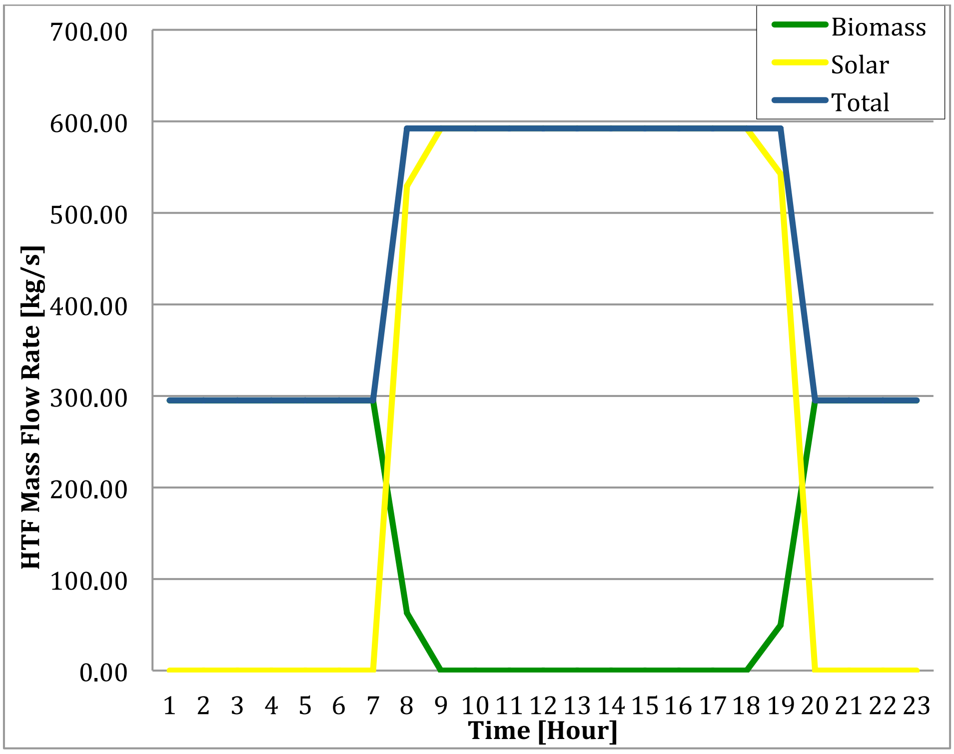

Figure 3.4: HTF mass flow rate on a clear day

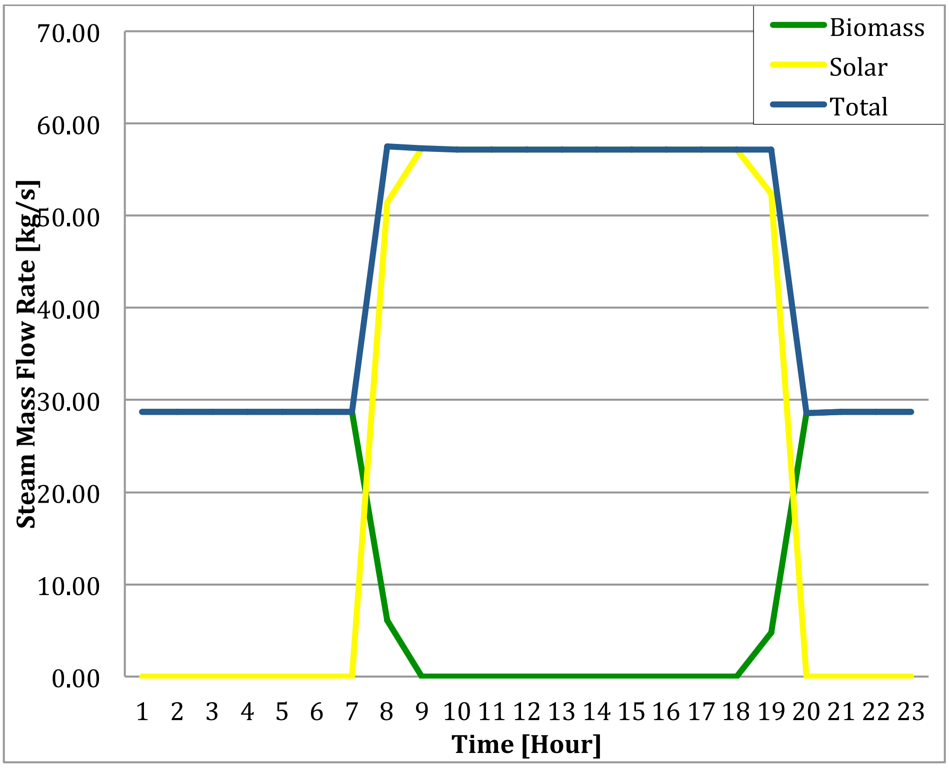

Figure 3.5: Steam mass flow rate on a clear day

3.2.3. Cloudy Day

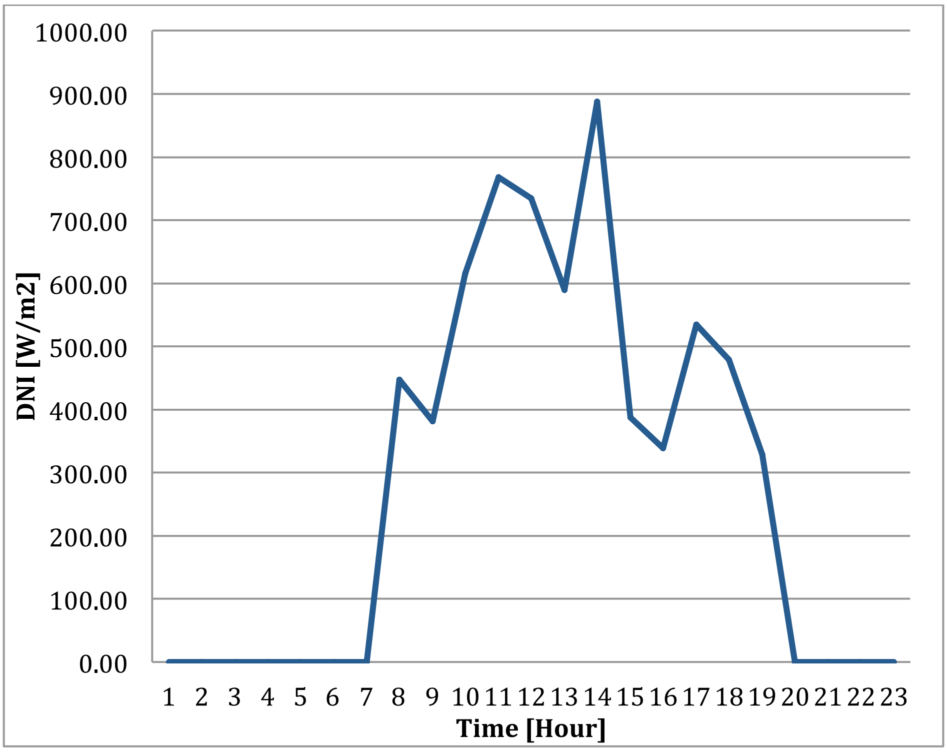

Figure 3.6: Direct Normal Irradiation (DNI) on a cloudy day

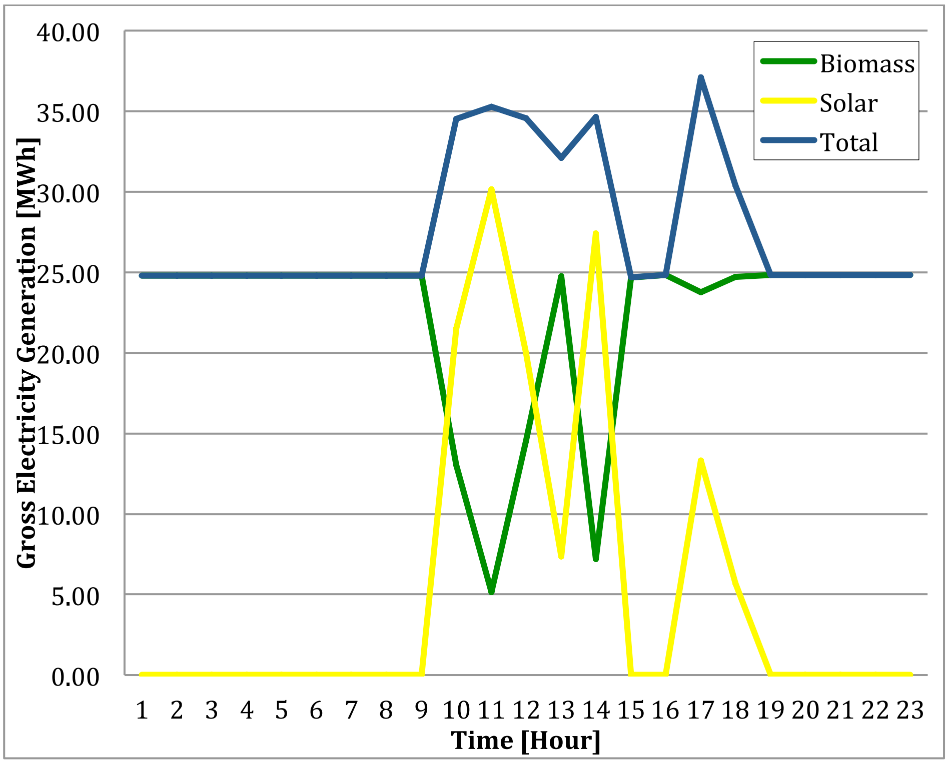

Figure 3.7: Gross electricity generation on a cloudy day

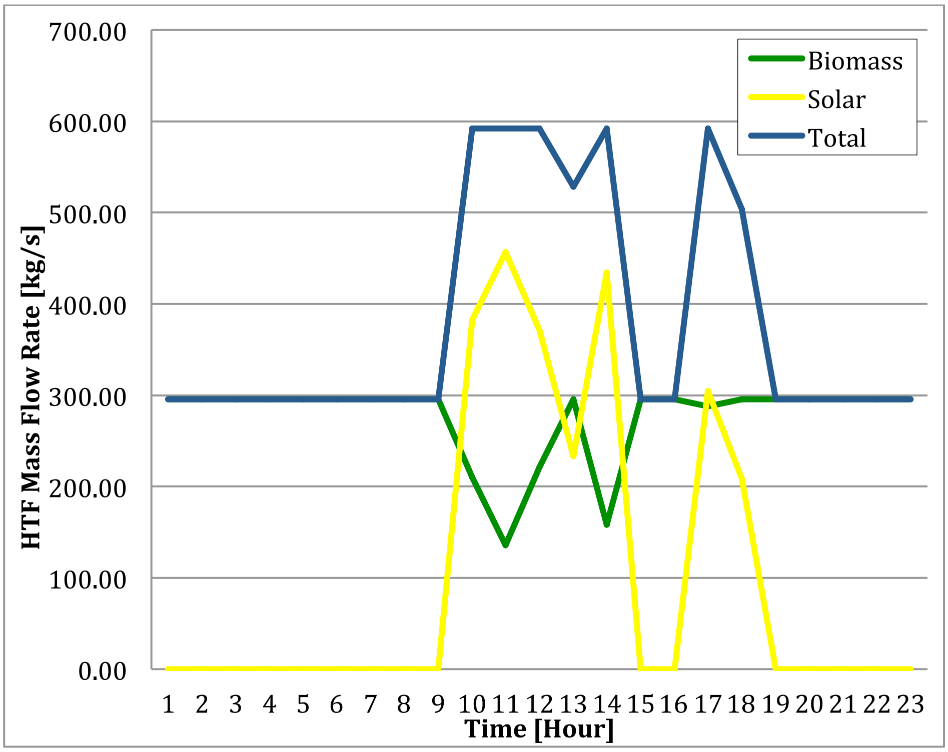

Figure 3.8: HTF mass flow rate on a cloudy day

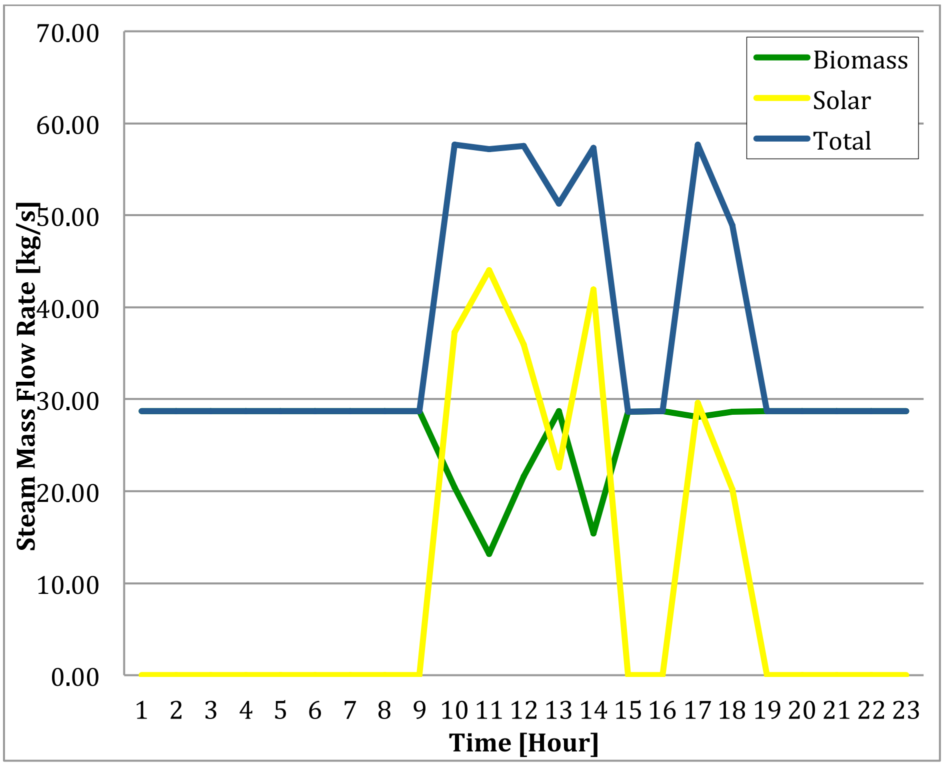

Figure 3.9: Steam mass flow rate on a cloudy day

3.3. Cost Analysis

Also for the upscaled 50 MW_e hybrid power plant some economic parameters are calculated, in order to complete the analysis of the simulated plant and integrate the annual operational results. Regarding the investment cost, it was already calculated for the 25 MW_e CSP-biomass hybrid power plant, as well as for two independents power plants based respectively on CSP and biomass combustion technologies having the same characteristics as the reference one, in order to assess the cost of implementing only one of the two technologies alone. The breakdown of the specific investment costs is shown in Table 2.8, for the three cases based on the three technologies. Resuming from Table 2.8, those are 6077 €/kW for a hybrid CSP-biomass power plant, 4597 €/kW for the CSP plant and 3334 €/kW for the biomass combustion plant. In the case of the upscaled 50 MW_e hybrid power plant, the same results can be utilized for calculating the total investment cost, having calculated the specific investment costs of the different technologies per unit of installed capacity, but taking into account that the upscaled plants' capital costs are increased by 1.75 times compared to the reference ones due to economies of scale. It is then assumed that for the CSP power plant, a gross installed capacity of 50 MW_e is considered, while for the Biomass power plant it is set to 25 MW_e, as twice the installed capacity of the biomass unit of the *Termosolar Borges*. In the end, the total investment cost of the upscaled power plant is 274 million €, still higher than in the other two cases, but still constituting a 23% saving compared to the simple addition of the two standard technologies.

Table 3.4: Comparative economic and performance assessment for three power plants based on CSP, biomass combustion and hybrid CSP-biomass technologies in the upscaled case

	CSP plant	**Biomass Combustion plant**	**Hybrid CSP-biomass plant**
Total Investment [€]	207000000	83400000	274000000
Operating Costs [€/year]	1269757	8524476	7136101
Eq. Hours of Operation [Hours/year]	1527	8016	6418
Biomass Consumption [Tonnes/year]	0	146666	123410
Net Electricity Generation [MWh/year]	68711	200400	197118
LCOE [€/MWh]	238.1	69.7	136.6

Regarding the LCOE, the second economic parameter to be analyzed, its value for the three cases is showed in Table 3.4 together with some performance parameters. Having doubled the size of the power plants for the three cases and obtained almost double the electricity generation, but with reduced capital costs due to the upscaled configuration, it can be noted that the LCOE is reduced with respect to the base case. As in the reference case, it may be concluded that the biomass combustion power plant provides the cheapest alternative, having an LCOE of 69.7 €/MWh, so it represents the most convenient alternative. However, this upscaled solution relies on the supply of a very large amount of biomass feedstock, estimated around 146666 tonnes/year, which far exceeds the quantity available locally in the region, around 60000-90000 tonnes/year [60].

This represents an even bigger challenge for the supply chain than in the reference case, keeping into account that also the highly volatile price of the biomass feedstock can represent a constraint during operation. Considering the hybrid CSP-biomass power plant, it is calculated an LCOE of 136.6 €/MWh, which is again almost twice the LCOE of the biomass combustion plant, but 57% lower than the conventional CSP plant. The biomass feedstock requirement is estimated around 123410 tonnes/year, an amount that far exceeds the quantity available locally as in the case of the biomass power plant. Considering the electricity generation, it is very close to the biomass combustion plant alternative. It can be concluded that if upscaled to 50 MW_e, the hybrid power plant reaches an electricity generation which is much higher than the CSP plant (2.86 times), increased hours of operation (4.2 times higher) and a much lower LCOE. The consumption of biomass feedstock is a bit high compared to the quantity available locally (i.e. 37% higher than the upper limit), but still the hybrid plant represents a cheaper alternative compared to the CSP power plant, with a better performance, showing the great potential of utilizing the biomass combustion technology for the hybridization of a CSP power plant.

3.4. Technical and Economical Comparison with Conventional 50 MW_e CSP Power Plants

After having obtained the performance parameters of the reference and the upscaled 50 MW_e hybrid power plants, and having analyzed the two plants also from an economic point of view, calculating some economic parameters such as the total investment costs and LCOEs, it is now possible to compare them with conventional 50 MW CSP power plants based on parabolic trough technology. This comparison is conducted to assess if the hybrid CSP-biomass configuration can be competitive with conventional CSP plants, both with and without TES, from both the point of views of the performance and economics. For this purpose, some Spanish CSP plants are selected as a reference, together with some other CSP plants situated in extra-European countries including India, South Africa, Kuwait and UAE. A list of these CSP plants is shown in Table 3.5, reporting the exact location of the plants and available DNI, the installed capacity, the aperture area of the solar field, the storage capacity, the expected electricity generation and the total cost. All the information regarding these plants are taken from the *National Renewable Energy Laboratory (NREL)* database at [61].

Southern Spain accommodates the great majority of the CSP power plants in operation today, having an average DNI of 1900–2100 kWh/m^2 year, and thus representing the most suitable location in Europe guaranteeing an increased electricity production for a power plant that relies entirely on solar resource [43]. It is interesting to notice how a hybrid CSP-biomass power plant as the *Termosolar Borges*, located in North East Spain within the region of average annual solar DNI of 1600–1800 kWh/m^2 year, with an installed capacity of 25 MW, is capable of generating 98000 MWh/year of electricity, approaching the electricity generation of conventional 50 MW CSP plants without TES characterized by expected outputs in the range of 100000-110000 MWh/year. Some exceptions are represented by *Lebrija 1* and *Orellana 1* power plants in Spain, and *Godawari Solar Project* plant in Northern India, with expected electricity generations respectively of 120000 MWh/year the first and 118000 MWh/year the other two. However, these increased generations are justified by the more favorable location of the plants and the oversized solar fields, around 2.2 times larger than the *Termosolar Borges*. This proves that it is possible to build such hybrid power plants in locations far away from optimal solar irradiation, as long as the availability of the required biomass feedstock is guaranteed. In the case of the *Termosolar Borges*, this does not represent a constraint for the supply chain, being the annual consumption equal to 62160 tonnes/year and the quantity available locally in the region around 60000-90000 tonnes/year [60].

If the results obtained indicate a very good performance of the hybrid power plant, it is even more interesting to continue the comparison from an economic point of view. In fact, the total investment cost of the *Termosolar Borges* is around 153 million €, 32% higher than an equivalent CSP power plant of 25 MW, but much lower if compared to 50 MW CSP plants without TES, which cost in the order of 225-280 million €. The reduced overnight costs, due to the reduced size of the hybrid plant, have a positive impact on its LCOE, which is 150.9 €/MWh_e, lower than the LCOE of conventional 50 MW CSP plant, in the range of 175-250 €/MWh (5% WACC case) [62]. So, it can be concluded that both from a performance and economic point of view, the 25 MW hybrid power plant represents already an excellent alternative to standalone CSP plants without TES, having a similar electricity generation and a lower investment cost and LCOE.

Table 3.5: List of Spanish and extra-European CSP power plants, with and without TES, with main technical and economic parameters

Year	Plant name and location	Latitude Longitude	DNI [kWh/m² year]	Plant Capacity [MW]	Aperture Area [m²]	Storage Capacity [hours]	Expected Output [MWh/year]	Cost [million €]
2009	**Ibersol Ciudad Real** Puertoellano	38.64N 3.97W	2061	50	287760	0	103000	200
2009	**La Risca** Badajoz	38.82N 6.82W	2174	50	352854	0	105200	230
2010	**Majadas I** Caceres	39.96N 5.74W	2142	50	372240	0	104500	237
2011	**Lebrija 1** Sevilla	37.003N 6.048W	1993	50	412020	0	120000	303
2012	**Olivenza 1** Badajoz	38.81N 7.06W	2107	50	402210	0	100000	284
2012	**Orellana 1** Badajoz	38.99N 5.54W	2133	50	405500	0	118000	240
2013	**Enerstar** Alicante	38.73N 0.92W	1907	50	339506	0	100000	225
2008	**Andasol 1** Granada	37.23N 3.07W	2136	50	510120	7.5	158000	310
2012	**Astexol II** Badajoz	38.81N 7.052W	2052	50	510120	8	170000	225
2012	**La Africana** Cordoba	37.74N 5.1W	1950	50	550000	7.5	170000	387
2013	**Arenales** Sevilla	37.15N 5.54W	2220	50	510120	7	166000	313
2013	**Casablanca** Badajoz	39.24N 5.31W	2061	50	510120	7.5	160000	345
2013	**Termosol 1** Badajoz	39.19N 5.58W	2054	50	523200	9	180000	409
2013	**Godawari Solar Project** India (North)	27.60N 72.00E	1895	50	392400	0	118000	103
2013	**Shams 1** United Arab Emirates (Abu Dhabi)	23.58N 53.71E	1934	100	627840	0	210000	600 USD
2014	**Megha Solar Plant** India (South)	16.99N 80.14E	1830 (1707)	50	366240	0	110000	105
2016	**Bokpoort** South Africa	28.78S 21.95E	2700 (2819)	55	588600	9.3	230000	565 USD
2017	**Shagaya CSP project** Kuwait	29.35N 47.68E	n.a.	50	n.a.	10	180000	n.a.

When introducing a TES system, the dispatchability and producibility of a CSP power plant increase dramatically, having the possibility to store excess energy in the form of heat for generating electricity during daily transients or during the night, when solar radiation is not available. In this case, a hybrid power plant as the *Termosolar Borges* shows some limits, especially in relation to the electricity generation which is much lower, due to the reduced size of the plant itself. On the other hand, it becomes very interesting to analyze how the upscaled 50 MW hybrid power plant behaves when compared to 50 MW CSP plants equipped with these impressive TES systems. In terms of electricity generation, the upscaled 50 MW hybrid power plant is capable of generating 197118 MWh/year of electricity, overcoming the electricity generation of conventional 50 MW CSP plants with TES characterized by expected outputs in the range of 160000-180000 MWh/year. The output can vary depending on the exact location (specific DNI), the storage capacity and the dimension of the solar field. A remarkable case is represented by *Termosol 1* power plant which, thanks to the good location and 9 hours of storage capacity, has an expected electricity generation of 180000 MWh/year. Having a look at extra-European CSP plants, *Bokpoort* power plant in South Africa should be mentioned: again, counting on a very high DNI compared to Spain, around 2800 kWh/m^2 year, and 9.3 hours of storage capacity, the plant is able to reach one of the highest expected electricity generation for a plant of its kind, around 230000 MWh/year. Anyway, it should be pointed out that the installed capacity of that plant is 55 MW, so the expected output is higher, but still it is an interesting case. The above-mentioned values of electricity generation prove that a 50 MW hybrid power plant, as the upscaled *Termosolar Borges*, has a great potential since, even if the location might not be ideal for CSP technology alone, combining it with biomass combustion technology can enable renewable generation in areas that might be less competitive otherwise. The only limit of such upscaled hybrid plant could be represented by the required amount of biomass feedstock, around 123410 tonnes/year. Being the quantity available locally in the province of Lleida around 60000-90000 tonnes/year [60], the supply could represent a constraint during the operation of the plant. Nevertheless, the closest provinces of Huesca and Barcelona count on a biomass availability of respectively 90000-120000 tonnes/year and 30000-60000 tonnes/year [60]. So, the supply to the hybrid plant could be guaranteed by the exploitation of those biomass resources, keeping into account that this would imply increased distances to be covered during the transportation phase, finally increasing the total cost of the tonne of biomass delivered to the plant.

Regarding some economic considerations, the total investment cost of the upscaled 50 MW hybrid power plant was calculated to be around 274 million €. If compared to 50 MW CSP plants with TES, which cost in the order of 310-410 million €, it can be noted that the cost is lower. This is a very interesting result, especially having simulated for the upscaled plant an expected electricity generation which is higher than the one of CSP power plants with TES. Again, as in the case of the *Termosolar Borges*, this is reflected in the LCOE: having increased the electricity output, but at the same time reduced overnight costs, the LCOE is reduced to 136.6 €/MWh$_e$, which is competitive with the LCOE of CSP plants with TES, in the range of 116-200 €/MWh (5% WACC case) [62]. With a better performance than a 50 MW CSP plant with TES, and a competitive LCOE, it can be concluded that the 50 MW hybrid power plant is an attracting solution as alternative to CSP plants hybridized with TES.

Some general conclusions can be resumed in the following points:

- The 25 MW hybrid power plant is capable of generating 98000 MWh/year of electricity, approaching the electricity generation of conventional 50 MW CSP plants without TES characterized by expected outputs in the range of 100000-110000 MWh/year.

- With an annual consumption of biomass feedstock equal to 62160 tonnes/year, there are no constraints to the supply chain, being the quantity available locally in the region around 60000-90000 tonnes/year [60].

- The reduced overnight costs of the 25 MW hybrid power plant, especially due to its reduced size, have a positive impact on the LCOE, which is 150.9 €/MWh_e, much lower than the LCOE of conventional 50 MW CSP plant, in the range of 175-250 €/MWh (5% WACC case) [62].

- The upscaled 50 MW hybrid power plant generates 197118 MWh/year of electricity, overcoming the electricity generation of conventional 50 MW CSP plants with TES characterized by expected outputs in the range of 160000-180000 MWh/year.

- The required amount of biomass feedstock, around 123410 tonnes/year, could represent a constraint during the operation of the plant, being the quantity available locally in the province of Lleida around 60000-90000 tonnes/year [60].

- The supply of biomass feedstock to the upscaled 50 MW hybrid power plant can be guaranteed by the exploitation of the biomass resources available in the nearest provinces. For instance, Huesca and Barcelona show a total potential of available biomass of 120000-180000 tonnes/year.

- Thanks to the hybridization, the reduced dimension of the solar field have a positive impact on the LCOE of the upscaled plant, around 136.6 €/MWh_e, which is competitive with the LCOE of CSP plants with TES, in the range of 116-200 €/MWh (5% WACC case) [62].

- In conclusion, the biomass combustion technology shows a great potential for the hybridization of CSP power plants, both from a technical and economic point of view, when compared to the actual alternative of very large and expensive TES systems.

4. Feasibility Study

In the previous section, the reference power plant was upscaled to a 50 MW hybrid power plant, having the same size of typical CSP power plants based on parabolic trough technology in Spain. A simulation of the plant was then conducted, using the same methodology as in section 2, to obtain the annual performance parameters of the plant, in order to carry out a technical and economical comparison between the reference 25 MW and upscaled 50 MW power plants with conventional 50 MW CSP power plants in Spain and outside Europe, with and without TES. In the end, it was possible to highlight the competitivity of the hybrid CSP-biomass configuration from the point of view of the performance, and economics, with conventional CSP power plants. Having obtained positive results, a feasibility study is conducted in this section. The final objective of this study is to assess in which extent the size of the hybrid power plant, as well as the availability and cost of the biomass feedstock in Spain, can affect its operation, and what is the potential of the biomass combustion technology for CSP hybridization also in extra-Spanish and extra-European contexts. First, the installed capacity of the hybrid power plant is increased, starting from 25 MW, in order to check which size of the plant would assure a sustainable supply of biomass to the plant without limiting its operation, at the same time guaranteeing better economic conditions. Then, a more economic analysis is conducted on the variation of the LCOE in relation to the price of the biomass feedstock, one of the most important parameters when evaluating the economics of only-biomass and hybrid power plants. Finally, the location of the hybrid power plant is changed to estimate how different climate and geographic conditions affect its electricity generation, the requirement of biomass feedstock and economics.

4.1. Hybrid CSP-Biomass Technology in Spain

The size of a biomass power plant has to be determined basing on several factors: some of the most important are the demand for electricity, the site conditions and amount of biomass residues available. Also some economic parameters have to be taken into account, including investment requirements, O&M costs and desired price of electricity to be sold [63]. It is proved that the cost of a biomass combustion plant tends to decrease as the system size increases, being the typical size of a power-only (not CHP) plant in the range of 5-25 MW. Larger systems require significant amounts of material, which can lead to constraints in the operation of the plant, but benefit from lower O&M costs per unit of energy generated and higher efficiencies than small systems [64]. In our specific case, being a biomass boiler utilized as hybridization system for the combustion of biomass residues, the same considerations made can apply to the case of the hybrid CSP-biomass power plant. If increasing the size of the hybrid power plant can lead to a higher electricity generation and lower LCOE, on the other hand the increased requirement of biomass feedstock can affect the supply chain and operation of the plant. In order to assess until which point the reference plant could be upscaled still assuring a sustainable supply of biomass, at the same time guaranteeing a better LCOE, a first feasibility analysis is conducted. This is performed varying the installed capacity of the hybrid plant from 25 to 50 MW by multiple of 5 MW, and calculating the relative annual consumption of biomass and LCOE. Then, the annual consumption is compared to the amount of available biomass in the region, and some considerations are made regarding the level of feasibility of each case. Figures 4.1 and 4.2 show a map of Spain with information about available forest biomass by province, the main component of the biomass feedstock utilized as fuel for the grate boiler, and the relative price for the tonne. This price includes harvesting and transport costs, all the costs before undergoing energy transformation [60]. Figure 4.3 finally show the different provinces of Spain.

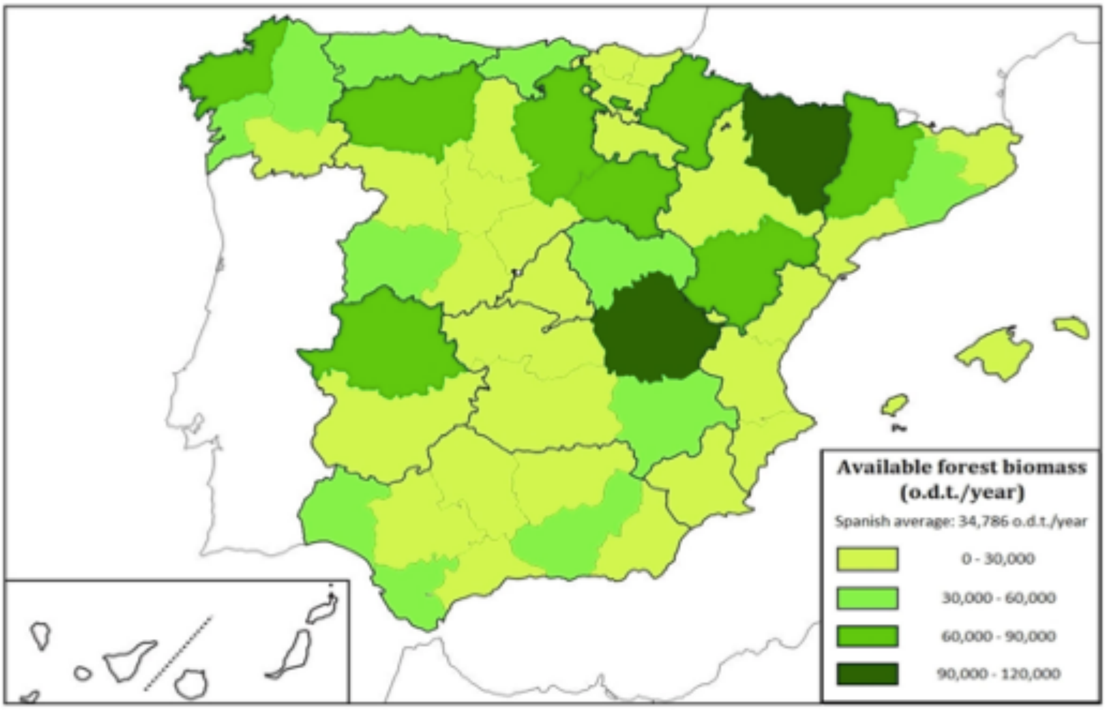

Figure 4.1: Available forest biomass in Spain by province [60]

Besides Lleida, another location is considered for the simulation of the hybrid power plant in order to estimate how different climate and geographic conditions affect the electricity generation, the requirement of biomass feedstock and economics of the plant. This is Sevilla, a city located in the region of Andalucia, at coordinates 37.06 N-5.15 W, characterized by an average DNI of 2222 kWh/m^2 year, higher than the average DNI of 1800 kWh/m^2 year of Northern Spain. The results obtained from the simulations are reported in Table 4.1 and 4.2, indicating the annual biomass consumption and LCOE for each plant size simulated at each location.

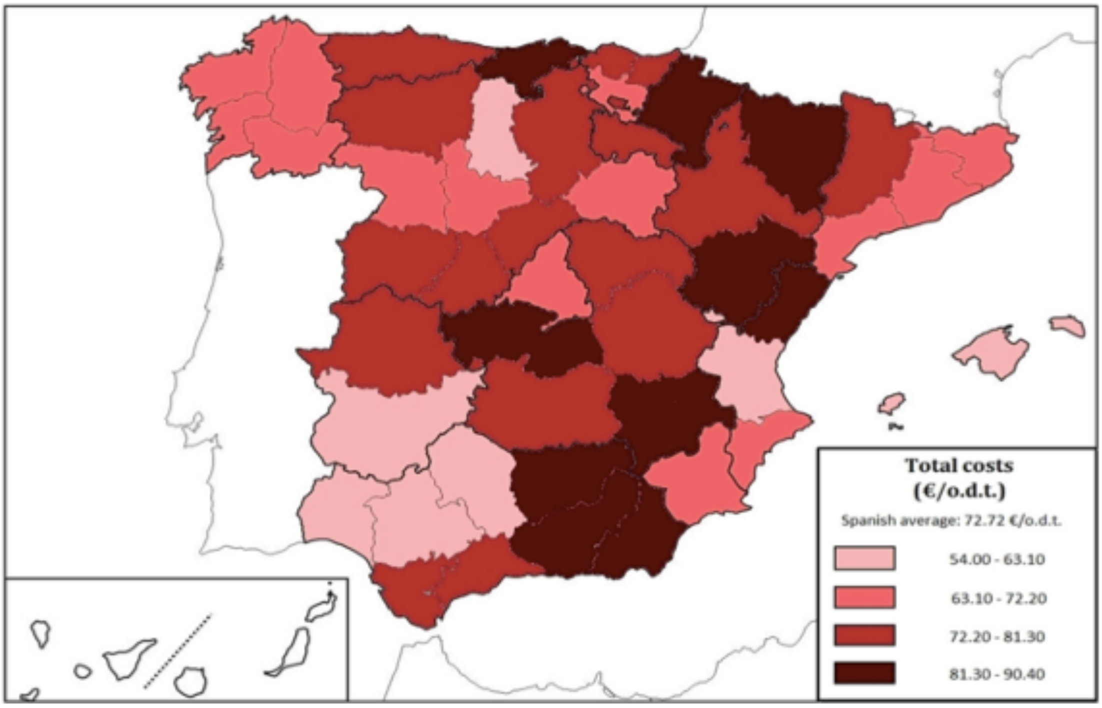

Figure 4.2: Total cost of forest biomass in Spain by province [60]

Figure 4.3: Provinces of Spain

As it can be noticed, in both cases increasing the plant size leads to a decrease of the LCOE, due to the increase in the electricity generation from both the CSP and biomass boiler, together with the reduced cost of equipment and O&M due to economies of scale. The 50 MW plant located in Sevilla shows the lowest LCOE, 127.53 €/MWh, 8% lower than the corresponding plant in Lleida with an LCOE of 136.61 €/MWh. This is mainly due to the higher DNI and lower dependency on biomass resource of the plant in Southern Spain. In both cases, thanks to the doubling of the installed capacity, a reduction of around 9-10% in the LCOE is obtained.

As a consequence of the increased generation from the boiler, the required amount of biomass feedstock increases until reaching 123410 tonnes/year in the worst case, corresponding to the 50 MW power plant located in Lleida. As already commented in the previous chapters, being the quantity available locally in the province of Lleida around 60000-90000 tonnes/year [60], the supply could represent a constraint during the operation of the plant. However, having a look at Figure 4.1, it may be noticed that the nearest provinces of Huesca and Barcelona count on a biomass availability of respectively 90000-120000 tonnes/year and 30000-60000 tonnes/year [60], so the supply to the hybrid plant in Lleida could be guaranteed by the exploitation of those biomass resources, and the plant size increased up to 50 MW, maybe even more. The situation is even worse considering the case of Sevilla: with only 30000 tonnes/year of forest biomass available in the region, the supply of the material could really represent a problem for the continuous operation of the plant throughout the year. Being the feedstock composed mainly by forest residues, with the addition of agricultural waste and energy crops [46], it can be concluded that upscaling the 25 MW plant would not make sense, affecting the continue operation throughout the year. It is interesting at this point considering that the largest biomass power plants in Spain are two, with a size of respectively 40 and 50 MW, situated in Huelva and operated by the *Ence* company [65]. The largest plant has an annual consumption of 366000 tonnes/year of forest residues and energy crops [66], very similar to the mix utilized by *Termosolar Borges* plant, which could appear pretty unsustainable especially looking at Figure 4.1, and after what was said previously. Again, this shows how this aspect can be easily managed to develop a solid supply chain for the biomass feedstock, also integrating biomass material from the closest provinces, and how it should be taken into account during the design phase of the plant for guaranteeing an optimal operation.

Table 4.1: Total net electricity generation, biomass requirement and LCOE for different installed capacities of a hybrid power plant in Lleida (Northern Spain)

Plant size [MW]	CSP generation [MWh_e]	Biomass generation [MWh_e]	Expected net generation [MWh_e]	Biomass requirement [tonnes/year]	LCOE [€/MWh_e]
25	34175	55384	98800	62160	150.96
30	41226	66028	118270	74046	147.76
35	48097	77032	137982	86387	144.63
40	54969	88037	157694	98728	141.56
45	61839	99042	177406	111069	138.56
50	68711	110047	197118	123410	136.61

Table 4.2: Total net electricity generation, biomass requirement and LCOE for different installed capacities of a hybrid power plant in Sevilla (Southern Spain)

Plant size [MW]	CSP generation [MWh_e]	Biomass generation [MWh_e]	Expected net generation [MWh_e]	Biomass requirement [tonnes/year]	LCOE [€/MWh_e]
25	42398	46939	98517	52681	141.92
30	51127	56036	118179	62891	138.92
35	59648	65375	137875	73372	135.97
40	68169	74714	157572	83854	133.09
45	76691	84054	177268	94336	130.27
50	85212	93393	196965	104818	127.53

If the problem of the supply chain for the material necessary to operate the biomass boiler can be solved, the utilization of biomass resources coming from outside the province where the plant is located would imply increased distances to be covered during the transportation phase, and an increased total cost of the tonne of biomass delivered to the plant, affecting the economics of the entire project. It is then interesting to analyze how the LCOE of the hybrid power plants is affected by different prices of the biomass feedstock, also considering the variability of the price of forest biomass in the different provinces of Spain, that can be appreciated having a look at Figure 4.2. A feasibility analysis is then conducted, varying the price of the tonne of forest biomass, and calculating the LCOE of the hybrid power plants under the different economic conditions. The results obtained from the simulations are reported in Table 4.3, indicating the annual O&M costs and LCOE for each biomass price simulated at each location, for a power plant size of 50 MW.

Table 4.3: Annual O&M costs and LCOE for different biomass prices of hybrid power plants in Northern and Southern Spain

	Lleida		Sevilla	
Biomass cost [€/tonne]	O&M [€/year]	LCOE [€/MWh$_e$]	O&M [€/year]	LCOE [€/MWh$_e$]
40	5134946	126.48	4715439	124.68
50	5801998	129.85	5277849	127.53
60	6469049	133.23	5840258	130.39
70	7136101	136.61	6402668	133.24
80	7903153	139.99	6965078	136.10
90	8470205	143.37	7527487	138.95
100	9137256	146.74	8089897	141.81

As it can be noticed, in both cases increasing the cost of the biomass leads to an increase of the LCOE, due to the increased annual O&M costs. From a base case of 40 €/tonne, with LCOEs of 126.48 €/MWh and 124.68 €/MWh respectively for the plants in Lleida and Sevilla, the plant in Southern Spain shows to be less sensitive to the variation of the price of biomass. In fact, an increase in the cost of 2.5 times, up to 100 €/tonne, leads to an increase of 17c€/MWh compared to the 21c€/MWh of the plant in Northern Spain. So, increasing the price of the biomass, it is more convenient to build the hybrid plant in Southern Spain, due to the lower dependency on the biomass resource. Anyway, the differences in the LCOEs of the two hybrid plants are not so relevant, confirming the potential of the hybrid technology especially in relation to those regions characterized by a lower solar resource.

A final interesting analysis can be conducted comparing the obtained results with the LCOEs of only-biomass power plants, which rely entirely on the biomass feedstock and are even more sensitive to the variations in its price. In the context of actual emission trading schemes that are increasing the cost of pollution, and so the carbon prices, some big utilities are repowering with sustainable biomass, and considering biomass power plants as a viable option for baseload power generation [67]. In this context of increased demand for biomass systems, the hybrid CSP-biomass technology shows to be a great alternative to only-biomass power plants. And the convenience is not only limited to sunny regions, but also to regions characterized by a lower solar resource. Table 4.4 reports the variation in the LCOE of an only-biomass power plant in relation to the price of the feedstock. In the same table, the ratios between the hybrid power plants and the only-biomass plant are shown, for each biomass price and for each location.

Table 4.4: Total net electricity generation, biomass requirement and LCOE for different installed capacities of a hybrid power plant in Sevilla (Southern Spain)

Biomass cost [€/tonne]	O&M [€/year]	LCOE [€/MWh$_e$]	$LCOE_{Lleida}/LCOE_{bio}$	$LCOE_{Sevilla}/LCOE_{bio}$
40	6163623	57.91	2.18	2.15
50	6950574	61.84	2.09	2.06
60	7737525	65.77	2.02	1.98
70	8524475	69.69	1.96	1.91
80	9311426	73.62	1.90	1.84
90	10098377	77.55	1.84	1.79
100	10885328	81.47	1.80	1.74

As it can be seen, only-biomass power plants are the most sensible to the variation in the price of the fuel: an increase in the cost from 40 €/MWh of 2.5 times, up to 100 €/tonne, leads to an increase of 24c€/MWh. This value shows how increasing the price of biomass, it becomes more convenient to build hybrid power plants, including the hybrid CSP-biomass plants analyzed in this work. In fact, the hybridization of CSP mitigates the effect of the increased prices for the renewable fuel. Regarding the potential in different locations, again Southern Spain appears to be the most convenient choice due to the higher DNI and lower dependence on the biomass resource of the hybrid plant. However, it can be seen from the results how, under the economic assumptions made for the simulations, the differences in the ratios for the hybrid plants built in Northern and Southern Spain are not so relevant; this confirms the potential of the hybrid CSP-biomass technology especially in relation to those regions of Norhtern Spain with a lower solar resource, an average annual direct solar irradiation of 1600–1800 kWh/m^2 year, compared to those regions of Southern Spain characterized by higher DNI, around 1800–2000 kWh/m^2 year, and more typically chosen for CSP projects.

4.2. Potential of the Hybrid CSP-Biomass Technology in European and Extra-European Countries

One of the key factors to the profitability of CSP projects, especially large-scale projects, is the expected electricity production of the plant. This is highly dependent on the direct solar irradiation; therefore the selection of a suitable location directly affects the economic viability of the capital investment [68]. It has been found in the previous sections that, even if the great majority of the Spanish CSP power plants are located within the average DNI range of 1800–2000 kWh/m^2 year [43], for a hybrid power plant an average annual direct solar irradiation of 1600–1800 kWh/m^2 year can be sufficient to assure a good performance. This expands the possible regions (in Spain and elsewhere) where CSP could be effective since even if the location might not be ideal for CSP alone, combining it with a well-situated biomass plant can enable renewable generation in areas that might be less competitive otherwise [46]. And many European regions, including among others Southern Italy, Southern France and Greece, become suitable for the implementation of the hybrid technology due to their particular condition of having acceptable amounts of DNI over the year, together with a good availability of biomass resources. In order to evaluate the potential of the biomass combustion technology for CSP hybridization in the above mentioned European countries, a first feasibility study is conducted in this section.

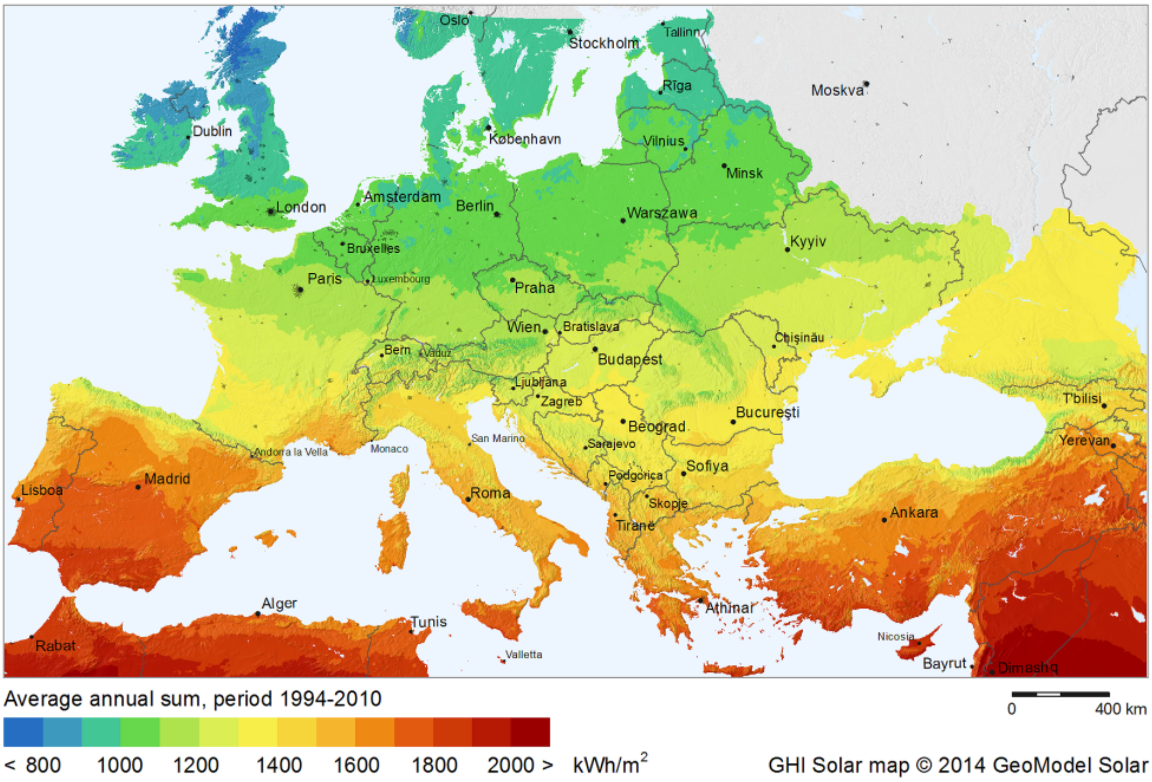

Figure 4.4: Direct Normal Irradiation (DNI) for different locations in Europe [69]

The study is conducted keeping the same investment costs and O&M costs as in the reference case of the *Termsolar Borges* power plant, and upscaled power plant, changing only the location of the plants and calculating the expected gross electricity generation, the relative consumption of biomass and LCOE. Consequently, the difference between the simulations relies only on the different climate and geographic conditions (i.e. specific DNI), very similar by the way. It is obvious that this approach is very simplistic; in fact, the adoption of renewable and clean energy technologies over non-renewable fuels is driving the development of CSP industry, but still great differences remain among the adopters of this technology in Europe and in the World [70]. The same applies to the Biopower industry, which is developing at different paces depending on the particular country, with different demand and prices for the biomass systems and feedstocks. Anyway, this approach allows a more homogeneous comparison, in relation to the reference case, for the new simulated hybrid power plants. Basing on the previous considerations, the general results obtained from the simulations are showed in Table 4.5, indicating the expected electricity generation, biomass consumption and LCOE for each 50 MW hybrid power plant simulated at each location. Figure 4.4 shows the DNI potential at different locations in Europe, and the values used for the simulations are reported in Table 4.5 for a quick comparison between the different cases.

Table 4.5: Average yearly DNI, expected gross electricity generation, biomass requirement and LCOE of hybrid power plants in different locations in Europe

Location	Latitude Longitude	DNI [kWh/m^2 year]	CSP generation [MWh$_e$/year]	Biomass generation [MWh$_e$/year]	Expected gross generation [MWh$_e$/year]	Biomass requirement [tonnes/year]	LCOE [€/MWh$_e$]
Foggia **Southern Italy**	41.60N 15.47E	1679	69266	128229	217895	129524	138.55
Salerno **Southern Italy**	40.03N 15.28E	1801	75500	122891	218791	124132	136.96
Bari **Southern Italy**	41.11N 16.85E	1839	78296	124487	223183	125744	134.61
Andravida **Greece**	37.93N 21.33E	1713	74702	124807	219909	126067	136.64
Carpentras **Southern France**	44.05N 5.05E	1754	73169	128673	222242	129972	135.96

As it can be seen from Figure 4.4, Italy has the highest levels of DNI among the above-mentioned countries, with peaks of around 1900 kWh/m^2 year in the region of Sicily. However, the power grid in Southern regions is weak for historical reasons, since these areas are less densely populated and larger consumption centers are located in the North [71]. So, the regions of Puglia and Campania were chosen as locations for the simulation of the hybrid power plant. With average DNIs in the range of 1700-1800 kWh/m^2 year, the results show a good performance of the hybrid plants, with expected gross generations around 218000 MWh/year, and LCOEs around 136 €/MWh. Bari shows the highest potential, with a gross electricity generation of 223183 MWh/year, 35% coming from the solar field, and an LCOE of 134.61 €/MWh. With a slightly lower DNIs, around 1700-1750 kWh/m^2 year, Southern France and Greece show also good results. With expected electricity generations of respectively 222242 and 219909 MWh/year, and LCOEs of 135.95 and 136.64 €/MWh, they also confirm the potential of the hybrid technology, performing very similarly to the reference plant of *Termosolar Borges* in Lleida. Regarding the biomass consumption, for all the cases it is in the range of 125000-130000 tonnes/year; fortunately, all the regions considered in this study are rich in biomass resources, mainly forest and agricultural residues, and do not present particular constraints to the biomass supply chain. However, if not supplied by local wood industries and agriculture residues, wood chips can also be imported. In particular, overseas imports from Latin America and the United States became competitive with local current supply chains [72].

The previous results clearly highlight the potential for the implementation of the hybrid technology in European countries, especially those characterized by levels of average DNI lower than the ones typical of conventional CSP projects. This is a very promising finding, especially in relation to the possible further development of the CSP industry in Europe. At this point, it might be interesting to analyze how hybrid CSP-biomass power plants would perform in extra-European countries, especially those charcaterized by higher levels of DNI, where CSP power plants are traditionally built with TES being this configuration the best from a technical and economic point of view. In order to assess how the performance of a hybrid power plant is affected by those higher levels of DNI, especially in relation to the potential for increased generation from the solar field and reduced requirement of biomass feedstock, as consequence of the variable contribution to the total electricity generation from the biomass boiler, a second feasibility study is conducted. This is performed by changing the location of the 50 MW hybrid power plant to extra-European locations. The new locations considered are Western United States, South Africa and Southern India. Regarding the motivation behind the choice of the above-mentioned locations for the new simulations, these were selected considering the level of development of the CSP industry in the different countries. Moreover, the potential for power generation from biomass and the availability of the same feedstock were considered as key factors, being the hybrid technology analyzed in this study closely related to both CSP and Biomass. The cases are singularly analyzed in the following chapters, briefly introducing the current deployment of CSP and biomass potential, finally analyzing the results obtained from the simulations highlighting the potential of the biomass combustion technology as a means of hybridization.

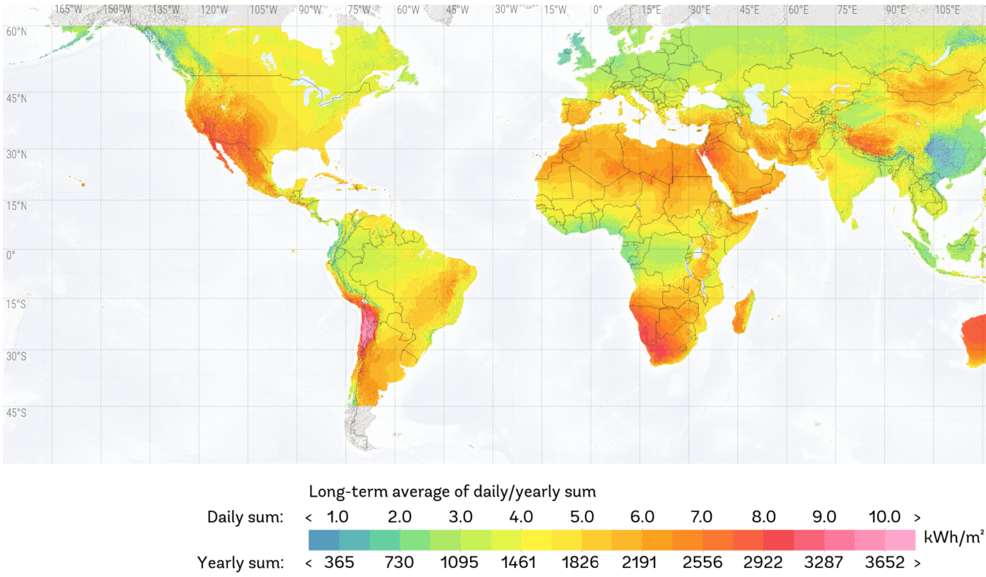

Figure 4.5: Direct Normal Irradiation (DNI) for different locations in Europe [69]

Table 4.6: Average yearly DNI, expected gross electricity generation, biomass requirement and LCOE of hybrid power plants in different locations in the World

Location	Latitude Longitude	DNI [kWh/m² year]	CSP generation [MWh_e/year]	Biomass generation [MWh_e/year]	Expected gross generation [MWh_e/year]	Biomass requirement [tonnes/year]	LCOE [€/MWh_e]
Bakersfield **California**	35.39N 119.04W	2702	102128	110450	232978	111565	126.48
Upington **South Africa**	28.44S 21.25E	2909	118498	94463	233361	95417	123.39
Geraldton **Australia**	20.14S 114.13E	2411	99989	112670	233059	113808	126.84
Anantapur **Southern India**	16.99N 80.14E	1830	80628	120792	221820	122012	134.72
Sevilla **Spain**	37.06N 5.15W	2222	94680	103770	218850	104818	133.24
Lleida **Spain**	41.10N 0.10E	1782	76346	122274	219020	123509	136.61

4.2.1 United States

With 1.7 GW of installed capacity in operation, the CSP industry is pretty well-established in the United States. The first CSP power plants, named Solar Energy Generating Systems (SEGS), were built in the 1980s in California. With a cumulative total capacity of 354 MW, they are the second largest solar thermal generating facility after the Ivanpah Solar Power Facility, which entered in operation in 2013 with a gross capacity of 392 MW, also in California [73]. And California is also the location chosen for the simulation of the hybrid power plant, due to the high available DNI but also the really high availability of biomass resources, estimated around 250000-500000 tonnes/year in the Bakersfield area, including forest and crop residues, primary and secondary mill residues [74]. The results of the simulation show an expected gross electricity generation of around 232978 MWh/year, 43% from CSP and 47% from biomass. Due to the high available DNI, around 2702 kWh/m^2 year, the share of electricity generation from CSP is increased with the consequent reduction of the biomass requirement. With an LCOE of 126.48 €/MWh, the hybrid technology shows to be competitive with the LCOE of current operating CSP plants, always keeping into account the economic assumptions made for the simulation. In fact, the lowest LCOE of an American CSP project was obtained by the 110 MW Crescent Dunes plant with 10 hours of storage, around 150 €/MWh [62].

4.2.2 South Africa

The CSP in South Africa is one of the most dynamic emerging markets in the World. After the renewed worldwide attention for CSP, the government of South Africa realized the levels of DNI were among the highest in Africa and the World, and the abundance of available, flat land, ideal for the application of CSP technology, convinced them to invest on it. With only 400 MW of installed capacity in operation, the country is constructing and planning CSP projects for 300 MW and more [75]. Moreover, the interest in biomass power generation is also growing, relying the country still heavily on fossil fuels, especially low-quality coal, and due to recent interest in reducing fuel emissions and decentralize electricity generation [76]. And regarding biomass availability, there are tonnes of available forest, agricultural and plantation residues, due to the not well-developed sector of Bioenergy in the country [77]. The region around Upington, in particular, has the highest levels of solar radiation, around 2909 kWh/m^2 year, so it was chosen as the location for the simulation of the hybrid power plant. The expected gross electricity generation of the simulated plant is around 233361 MWh/year, 51% from CSP and 41% from biomass. In this case, the effects of the higher DNI are even more relevant than in the case of California, with the biomass requirement sensibly reduced from the reference case by 23%. The LCOE of 123.39 €/MWh clearly shows the potential of hybrid power plants for a country so interested in investing in both CSP and biomass for power generation.

4.2.3. India

With only 225 MW of installed capacity in operation and other 292 MW under construction, the CSP industry in India has just started its process of growth. Coal still supplied 80% of

India's total power mix in 2016-2017, but while India's power demand will double over the next decade, its draft National Electricity Plan (NEP) calls for rising demand to be met with 275 gigawatts (GW) total renewable energy capacity by 2027, without requiring new coal plants beyond those already under construction (around 50 GW), at the same time closing nearly 50 GW of coal capacity by 2027 [78]. And in this context of energy transition to renewable energies, the Jawaharlal Nehru National Solar Mission launched on the 11th January 2010 by the Prime Minister set an ambitious goal of deploying 20 GW of solar capacity by 2022 [79]. India has levels of DNI very close to Northern Spain, around 1700-1800 KWh/m^2 year, with peaks of 1900-2000 KWh/m^2 year in the extreme Northwest of the country (Rajasthan) [80]. The available DNI makes CSP projects feasible, especially in the Rajasthan region, but moving from that area the performance of conventional CSP plants decreases strongly, due to the lower solar resource. Moreover, India has a huge amount of agriculture land area, with massive residues produced every year, around 500 million tonnes/year, with around 120-150 million tonnes unused [81]. So, there is clearly a great potential for developing decentralized hybrid CSP-biomass power plants around the country, especially being transport one of the main barriers today to the deployment of an efficient biomass supply chain. The results of the simulation show, for the hybrid plant, an expected gross electricity generation of around 221820 MWh/year, 37% from CSP and 55% from biomass. Being the available DNI, around 1830 kWh/m^2 year, very similar to the one of Lleida in Northern Spain, the share of electricity generation from CSP and biomass are almost the same as in the case of the *Termosolar Borges*. Also the LCOE of 134.72 €/MWh is close to that of the Spanish hybrid power plant, indicating Central India as a potential area of implementation of the competitive hybrid technology due to the similar climate and geographic conditions.

5. Business Potential

The solar industry is undergoing a serious and continuous development, becoming very attractive from a business standpoint. Some emerging markets are driving today the development of CSP technology worldwide, namely China, India, Northern and Southern Africa, Middle East [14]. This represents a massive opportunity for European multinational energy companies, which could take the lead in the process of developing the innovative hybrid technology in the above-mentioned countries, especially those already present in the CSP industry and more experienced. Also at a European level, the potential for the hybrid technology is high: hybrid solar-biomass plants may be an alternative option for RE generation for those regions where the solar resource is moderate but biomass resources are readily available [43], unlocking new market opportunities. Even if CSP is now limited to the areas around the "sun belt", the hybrid concept could make it evolve into an affordable and scalable alternative to conventional power generation at competitive levels, representing the only RE option able to provide both base and peak-load, when deployed as alternative to actual expensive TES systems [10]. The large-scale deployment of such innovative hybrid technology could induce various benefits such as energy security, climate protection, income from exports of electricity as well as components and services, private sector development and job creation [82]. In this chapter, all these aspects, including the keys for a sustainable development of the industry in Europe, will be analyzed.

5.1. R&D and Innovation: a Business Opportunity for ABANTIA and COMSA EMTE

The world's demand for energy grew by 2.1 percent in 2017, more than twice the previous year's rate, according to new data from the International Energy Agency (IEA). Boosted by a strong economic growth, India and China accounted for over 40 percent of last year's rise in demand [83]. However, many more countries are participating to this tremendous increase in the demand, including Northern and Southern Africa and the Middle East, with MENA region showing a rate of increase of 6-8% per year, and a demand expected to double by 2020 and triple by 2050 [82]. In this context, and with an increasing pressure in meeting international goals for climate mitigation, RE systems able to generate a large amount of renewable electricity gain even more importance, with CSP representing one of the most promising technologies. In the field of CSP, Spain represents one of the leading countries in Europe and in the World, together with the United States, with 2.3 GW of installed capacity at the end of 2017 [14]. During the expansion of the CSP industry in Spain, many companies were able to specialize in the development and construction, operation and maintenance of CSP projects, including among others *Abengoa Solar*, *Acciona*, *SolarReserve* and *Torresol Energy*. However, when considering the hybrid CSP-biomass technology, with only one plant in operation worldwide, the reference companies are limited to the two *Abantia* and *COMSA EMTE*. Being the hybrid technology attracting for many features, as stated several times throughout the report, having participated in the realization of the *Termosolar Borges* power plant put the two companies in a privileged position. As a consultancy company focusing its work in six different business areas, including the area of R&D (*Abantia I+D+i*) [84], the potential for *Abantia* for keeping investigating in the hybrid technology and its possible applications is huge. *COMSA EMTE* is more involved in the O&M of the plant situated in Lleida, providing the required biomass necessary for the operation of the plant and treating it on-site before its utilization as fuel [85]. Taking part in the operation of this one-of-a-kind power plant, the possibility to improve even more the provided services represents a unique opportunity for the group. So, the R&D potential related to the hybrid CSP-biomass technology is massive and represents an important opportunity for the above-mentioned companies.

As the Spanish firm *Abengoa,* that has been one of the most successful in deploying CSP plants around the world, including several large projects in the U.S. (e.g. the 280 MW Solana Generating Station), *Abantia* might follow the same line offering project development, project management, engineering, procurement and construction in one package related to the CSP-biomass technology for hybrid generation. As stated above, the CSP industry is expected to grow in the MENA region, characterized by a very developed olive oil industry [82]. After having proved the reliability of the biomass combustion boiler configuration, moving to the development of a biomass gasification boiler, able to handle olive oil residues as feedstock, would represent a very attracting opportunity. This is only one example of many possible directions towards which R&D might evolve, with many possible new components and configurations that could be developed and commercialized, representing new market opportunities for the company.

Considering Europe as a whole, it offers a strong technology base, being home to some of the world's leading multinational energy and systems integration companies, as well as many smaller research institutions and specialized companies. The development of such hybrid systems requires critical mass plus multidisciplinary skills and innovations. The networking teams and efforts are more important than individual concrete actions to make a breakthrough and achieve success in research and development, demonstration and commercialization. Integration of partners together over Europe would provide to joint R&D projects a wide flexibility to minimize the technical risks and enhance its success. The possibility to integrate experts from bioenergy, solar energy, power generation, economics, as well as SMEs, hardly available in one country, would represent an added value. This projects would provide know-how for all partners which can be applied as the markets grow, as well as patents, stimulating the "clean energy" economy.

5.2. Europe and Hybrid CSP-Biomass Technology: Unlocking New Markets

Key to the profitability of CSP projects, especially large-scale projects, is the expected electricity production of the plant. This is highly dependent on the solar irradiation; therefore the selection of a suitable location directly affects the economic viability of the capital investment [68]. Most of the European CSP power plants in operation are typically located within the average DNI range of 1800–2000 kWh/m^2 year [43]. Regions included in that DNI range are southern Turkey, southern Portugal and southern Spain. The last one, in particular,

accommodates the great majority of the CSP power plants in operation today, being the most suitable location for increasing the electricity production of the power plants, consequently reducing their levelized cost of electricity and increasing their reliability and feasibility. However, DNI below that range may be useful for hybrid technologies [43]. For instance, the world's only hybrid solar biomass power plant is located in North East Spain, within the region of average annual direct solar irradiation of 1600–1800 kWh/m^2 year. With a continuous, stable electricity generation of around 98000 MWh/year during its first years of operation, *Termosolar Borges* proved that it is possible to build such hybrid power plants in locations far away from optimal solar irradiation. A similar result expands the possible regions (in Spain and elsewhere) where CSP could be effective since even if the location might not be ideal for CSP alone, combining it with a well-situated biomass plant can enable renewable generation in areas that might be less competitive otherwise [46]. The possibilities do not become infinite, but still many regions in Europe become now suitable, and many markets for hybrid CSP and biomass technologies disclosed, including among others Turkey, southern Italy and southern Greece. It must be added that due to their unconventional configurations, hybrid solar-biomass power plant should be located in a place where not only solar irradiance is good but where there is also a good availability of biomass resources since a backup is needed when there is insufficient solar thermal energy [43].
And the potential of the hybrid technology is not limited just to the construction of new power plants, but also to the retrofit of existing ones. Recently the Italian developer *Falck Renewables* retrofitted an existing 14 MW_e biomass power plant that was originally built in 2000, by converting it into a hybrid biomass-CSP plant [86]. Realized in Cambria (Italy) it is a low-temperature hybrid that use Fresnel as CSP technology, operating at 300°C and using virgin wood as the biomass feedstock. Retrofitting an older renewable project to a hybrid with another renewable like the *Falck* plant does make sense, but Fresnel plants are relatively few, so the real potential relies on older parabolic trough plants. The main benefit of such a retrofit would be being able to operate the plant more hours per year, increasing the efficiency of the power plant itself since the power block it is used for longer hours per year [86]. In this sense, from an investment point of view, a hybrid is more efficient than a pure CSP plant and the potential of retrofitting old and inefficient existing power plants could represent the next big market opportunities for the companies operating in the CSP and Biomass sectors.

5.3. Macro Socio-Economic Benefits

A competitive CSP industry would have a positive impact on the socio-economic development of the countries. Job creation and GDP increase are the main positive outcomes from this perspective. Direct job creation is expected during construction and operation of the plant, which represents the biggest job creator. Indirect jobs can arise from increasing demand in the supply chain, while induced jobs are related to the effects such as consumption of good and service on working sites. In the *Plan de Energias Renovables 2011-2020* [56], it was forecasted that for the year 2020 the field of renewables energies in Spain would generate around 303000 jobs (direct and indirect). The CSP industry would account for 6.1% of the total, around 18500 jobs, while the Biopower industry for 16.3%, around 49400 jobs.

Considering also the planned CSP capacity for the same period, around 4170 MW [87], we obtain a full-time equivalent job ratio of 4.4 jobs/MWp for the CSP technology including manufacturing, contracting and installation and O&M. Analyzing the particular case of the *Termosolar Borges*, from the available data it can be observed that the hybrid power plant created approximately 350 jobs during construction, plus 30 direct and 50 indirect jobs during operation [88]. It means 14 jobs/MW during the construction and assembly, plus 1.2 direct and 2 indirect jobs (3.2 in total) per MW installed generated by the O&M of the plant.
Direct economic effects are related to the construction of the plant, while indirect effects are from demand in the supply chain. Induced effects can arise from a higher consumption due to the increased wealth. All these aspects can contribute to a growth of the GDP. The development of CSP industry based on an innovative technology, as it is the hybrid one, would be beneficial under all the aspects for any country. Regarding Spain, it would place the country in a favorable position to be globally competitive and leader in the exports for specific systems and services. Furthermore, job creation and economic growth are the main local benefits for the interested countries. The CSP technology is a technology able to effectively involve the local population, in a process of innovation towards a more sustainable future, boosting local industry and developing the local manufacture sector.

5.4. Energy Independence and Energy Diversification

The external energy dependency of a country constitutes a structural deficiency, is a source of high commercial deficit and a latent factor of instability. Considering Spain, in 2015 the external energy dependency was about 73%, superior to that of the European Union, around 52%, and most of the Western countries [89]. In this context, it is clear that the diversification of the energy sources of the country, together with a reduced dependency on energy imports from other countries, can bring stability to the national economy and contribute to reducing the commercial deficit of the national balance of payments. In the case of RE systems, the effect is even more important, producing relevant environmental benefits and putting the country on the path for a long-term sustainable development. It should also be pointed out that investing in new renewable generation capacity would allow Spain to increase its income from electricity exports, thanks to the very strategic location of the country, representing the only real physical connection between Europe and Northern Africa.

5.5. Environmental Benefits

With an increasing pressure in meeting international goals for climate mitigation, considering the environmental, social and economic consequences of climate change, and the fact that production and consumption of energy are the main responsible for greenhouse gas emissions, RE systems able to generate a large amount of renewable electricity gain even more importance [90]. In fact, the energy sector is highlighted as the key to achieve the environmental objectives, with CSP representing one of the most promising solutions. The use of renewable energies presents multiple advantages of environmental type compared to the use of other sources, such as fossil fuels and nuclear energy. Although the environmental benefits of the use of renewable energies affect a large number of pollutants, it is common to relate to carbon dioxide, being the main greenhouse gas. In the *Plan de Energias Renovables 2011-2020* [54], it was forecasted that for the year 2020 the field of renewables energies in Spain would avoid around 32 Mt of CO_2, becoming around 170 Mt if the entire period 2011-2020 is considered. The CSP industry would account for 16.9% of the total in 2020, around 5.52 Mt, while considering the period 2011-2020 the total avoided emissions would be around 32.5 Mt, the 19% of the total. The numbers increase even more if we take into account the already existing RE systems in operation before the year 2011. Analyzing the particular case of the *Termosolar Borges*, in the available data it is reported that the hybrid power plant will avoid 24500 t of CO_2 during its operation [88]. So, the potential of the CSP industry in relation to climate mitigation is clear, and if we consider hybrid CSP-biomass technology it increases even more, motivation that should foster the development of this innovative technology towards a more sustainable future.

6. Summary, Conclusions and Future Research

In the present work, the potential for biomass hybridization of CSP power plants, based on parabolic trough technology, has been analyzed. CSP has shown its ability to integrate with fossil fuel-based generation sources in “hybrid” configurations, and Integrated Solar Combined Cycles (ISCC) power plants are just one example. Also, completely renewable hybrid systems are possible if hybridization is realized integrating CSP with the well-known biomass combustion technology. Concentrating solar power (CSP) represents one of the most attracting renewable energy technologies. It presents the great advantage, when compared with other RES, of providing both firm and dispatchable electricity, especially when deployed with thermal energy storage (TES) systems, being a valid alternative to both renewable hydropower plants and conventional fossil fuel-based power plants. Its implementation is only limited by the available solar resource, specifically the Direct Normal Irradiation (DNI), making it a feasible solution only in the areas around the “sun belt”, characterized by high values of DNI, above 2000 kWh/m^2 year. In contrast, hybrid CSP-biomass power plants only need around 1700 kWh/m^2 year of average DNI, extending the areas of application of CSP technology, and representing a great alternative for hybridization compared to expensive CSP deployed with TES, as shown in the results of this work. The integration of the biomass boiler into the CSP power plant, thanks to their complementarity as primary energy resources, lead to the advantages of improving the flexibility and competitiveness of the power plant, increasing its electrical efficiency and number of equivalent operating hours, finally improving the overall performance of the power plant and reducing its capital costs and LCOE.

The analysis of the hybrid technology is conducted in this work through the numerical simulation of the only existing hybrid CSP-biomass power plant in the world, the *Termosolar Borges* located in Lleida, Spain. The modeling and simulation of the hybrid plant, performed through TRNSYS software, allows the collection of important technical and economic information regarding the operation of the plant. After proper validation of the model, comparing the results obtained with the reference data, the same is used to do the upscaling of the reference plant up to 50 MW, the typical size of a CSP plant in Spain, and simulate it. The results of the simulations show that the 25 MW hybrid plant, characterized by an average DNI of 1780 kWh/m^2 year, is capable of generating 98800 MWh/year of electricity, being competitive with conventional 50 MW CSP plants without TES, characterized by average DNI of 2000 kWh/m^2 year and higher, and expected outputs in the range of 100000-110000 MWh/year. The overall results obtained, close to the values of the reference data, confirm the validity of the model for the simulation of the hybrid plant. Although the installed capacity of the hybrid plant is only 25 MW, half of conventional CSP plants, the number of equivalent operating hours is higher, around 6442 hours, due to the continuous operation of the power block, also during night time and transients, thanks to the utilization of the biomass boiler. With an investment of 153 million €, the LCOE obtained is 150.9 €/MWh$_e$, lower than the LCOE of conventional 50 MW CSP plant without TES, in the range of 175-250 €/MWh. Despite the specific investment cost for the hybrid power plant is higher than in the other two cases, there is a 23% saving compared to the simple addition of the two standard technologies, thanks to the shared components during the operation of the plant. Regarding the upscaled 50 MW hybrid power plant, it is capable of generating 197118 MWh/year of electricity, overcoming the electricity generation of conventional 50 MW CSP plants with TES characterized by expected outputs in the range of 160000-180000 MWh/year. With an investment of 274 million € and an LCOE of 136.6 €/MWh$_e$, competitive with the investment and LCOE of CSP plants with TES, respectively in the range of 310-410 million € and 116-200 €/MWh, the 50 MW hybrid power plant shows to be a very attracting investment with even a better performance. The requirements of biomass feedstock, respectively of 62160 tonnes/year and 123410 tonnes/year for the 25 MW and 50 MW cases, do not represent a constraint to the operation of the plants, as long as the supply from the closest regions is guaranteed.

The feasibility study highlights how the economics of hybrid power plants are highly dependent on the price of the biomass feedstock: an increase of its cost from 40 €/tonne to 100 €/tonne determines an increase of the LCOE from 126.48 €/MWh$_e$ to 146.74 €/MWh$_e$, for the 50 MW hybrid plant case, due to the increased O&M costs. However, with growing biomass prices, it becomes more convenient to build hybrid power plants, including the hybrid CSP-biomass plants analyzed in this work, especially as an alternative to biomass only power plants. In fact, the hybridization of CSP mitigates the effect of the increased prices for the renewable fuel.

The DNI also affects the performance of hybrid power plants. Even if high DNI increase the profitability of CSP projects, an average DNI in the range of 1600–1800 kWh/m^2 year has proved to be sufficient to assure technical and economic feasibility. This extends the potential of implementation of the hybrid technology to European countries characterized by lower levels of DNI, but good availability of biomass resources. The results clearly show that Southern Italy, Southern France and Greece represent suitable locations for such hybrid power plants, with gross electricity generations in the order of 218000-222000 MWh/year and LCOEs in the range of 136-139 €/MWh. Also at World level, the implementation of the hybrid technology in countries with higher DNI, where CSP power plants are traditionally built with TES as a means of hybridization, is feasible. California, Southern India and Southern Africa show how the higher levels of DNI allow higher gross electricity generations, in the order of 221000-233000 MWh/year, and lower LCOEs, around 126-136 €/MWh. While Southern India shows results very similar to the plant simulated in Lleida, South Africa shows the greatest potential, with an LCOE getting as low as 123.39 €/MWh especially due to the reduced biomass consumption, around 95417 tonnes/year. However, CSP plants with TES still represent the best choice in countries with very high DNI, above 2500 KWh/m^2 year.

CSP technology is experiencing a sort of renaissance today, being its development driven by some emerging markets worldwide, such as India, Northern and Southern Africa, Middle East and China. This represents a massive opportunity for European multinational energy companies, especially those already present in the CSP industry and more experienced, to take the lead in the process of developing the innovative hybrid technology in the above-mentioned countries. Due to the low level of R&D, many Spanish and International companies could take advantage, investing in R&D in the early stage of deployment of this attracting technology, counting on their expertise and know-how in the CSP field. The large-scale

deployment of such innovative hybrid technology could induce various benefits also at a country level, such as energy security, climate protection, income from exports of electricity as well as components and services, private sector development and job creation.
The hybrid power plant under study has proven to be feasible and reliable. However, some interesting points could be further analyzed, in order to increase even more the competitivity and attractiveness of the emerging CSP-biomass technology:

- The hybridization operation mode at the *Termosolar Borges* plant is performed through a biomass combustion boiler, which uses mainly forest residues, with the addition of agriculture waste from grapes, fruit trees and corn. This solution is based on the well-known and commercially available biomass combustion technology, which has shown to be reliable and efficient. However, as means of hybridization, biomass gasification boiler is another attracting solution. As emerging alternative for power generation, it shows the great advantages over direct combustion of lower emissions and the ability to handle a wider range of biomass feedstocks and waste fuels, including olive oil residues. Indeed, the olive oil industry is very developed in Spain and other Mediterranean countries, generating large amounts of solid residues that can be used as feedstock.

- The potential of the hybrid technology could be extended not only to new CSP-biomass power plants but also to the retrofit of existing ones. Retrofitting an older renewable project to a hybrid with another renewable does make sense, but it is crucial to properly match the biomass feedstock and the specific CSP technology, due to the different temperature requirements. The benefits of such a retrofit would be being able to operate the plant more hours per year, increasing the efficiency of the power plant itself since the power block it is used for longer hours per year. From an investment point of view, a hybrid is more efficient than a pure CSP plant and the potential of retrofitting old and inefficient existing power plants could represent the next big market opportunities for the companies operating in the CSP and Biomass sectors.

- In the context of sustainability and reduced environmental impact, Municipal Solid Waste (MSW) might be an attracting option as feedstock, especially due to the recent rising costs of landfills in Europe, mainly due to higher taxes for landfilling. Both direct combustion (incineration) and gasification are suitable choices for the generation of electricity using MSW, with the latter showing higher efficiencies over the former. However, it should be taken into account the more complex O&M of the plant, especially due to the pre-treatment of the feedstock and more complex operation of the boiler.

In conclusion, the present work highlighted the potential of the hybrid CSP-biomass technology. Technical, social, economic and business-related aspects have been considered. Even if CSP is now limited to the areas around the “sun belt”, the results obtained highlight that the hybrid technology could make it evolve into an affordable and scalable alternative to conventional power generation worldwide and at competitive levels, representing the only alternative to actual complex and expensive TES systems, towards a more sustainable and decarbonized electricity sector.

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Annexes

Annex I: Calculation of the total investment cost and specific cost for the three power plant based on CSP, biomass combustion and hybrid CSP-biomass technologies

The following is a particular of the excell sheet utilized for the calculation of the total investment cost and specific cost of the three power plants based on the different technologies under study, in the case of a total installed capacity of 25 MW.

Component	Specific Cost [€/kW]	Total Cost [€]	Component	Specific Cost [€/kW]	Total Cost [€]	Component	Specific Cost [€/kW]	Total Cost [€]
			Biomass Treatment Plant	600	7500000	Biomass Treatment Plant	500	7500000
			Biomass Boiler	1200	15000000	Biomass Boiler	1200	15000000
Solar Field	1831	45780000				Solar Field	1831	45780000
Heat Recovery Boiler	400	10000000				Heat Recovery Boiler	400	10000000
Heat Transfer System	586	14649600				Heat Transfer System	879	21974400
Turbogenerator Set (incl. Condens)	400	10000000	Turbogenerator Set	400	5000000	Turbogenerator Set	400	10000000
BOP	120	3000000	BOP	120	1500000	BOP	120	3000000
Civil Works	366	9156000	Civil Works	366	4578000	Civil Works	366	9156000
Subtotal		92585600			33578000			122410400
Contingencies		6480992			2350460			8568728
Total Direct Costs		99066592			35928460			130979128
EPC & Owner Costs		10897325,12			3952130,6			14407704,08
Total Indirect Costs (incl. sales tax)		15850654,72			5748553,6			20956660,48
Total Installed Costs		**114917246,7**			**41677013,6**			**151935788,5**
Total Specific Cost	**4597**			**3334**			**6077**	

if sum of the two	7930,9	156594260,3
saving of hybridization	1853,4	4658471,8
saving of hybridization [%]	23,4	

Annex II: Calculation of the different O&M costs of the 25 MW_e *Termosolar Borges* power plant

The following is a particular of the excell sheet utilized for the calculation of the O&M costs in the case of the reference 25 MW hybrid power plant. The same calculations are performed in the case of the 25 MW standalone solar and biomass power plants, as well as for the three 50 MW upscaled power plants (based on solar, biomass or hybrid). The O&M costs are then used for the calculations of the LCOEs of the plants.

	LLEIDA													
		SOLAR			*BIOMASS*									
year	(1+i)^n	Egen_solar	Co&m_fix	Co&m_var	Egen_bio	Egen_ng	Egen_tot	Co&m_fix	Co&m_var	C_bio	C_ng	C_el_PPA	C_n	NPV
0	1,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00		-151935788,48
1	1,06	75944608,00	1230805,69	230353,31	123077486,00	20400000,00	219422094,00	1857819,91	373315,60	8248766,36	725118,48	47161633,65	34495454,31	-117440334,17
2	1,11	75564884,96	1166640,46	217252,65	122462098,57	20298000,00	218324983,53	1760966,73	352084,38	7818735,88	683879,52	44479455,43	32479895,81	-84960438,37
3	1,17	75187060,54	1105820,34	204897,05	121849788,08	20196510,00	217233358,61	1669162,78	332060,62	7411124,06	644985,90	41949818,16	30581767,40	-54378670,96
4	1,24	74811125,23	1048170,94	193244,14	121240539,14	20095527,45	216147191,82	1582144,82	313175,66	7024762,14	608304,23	39564046,51	28794244,58	-25584426,38
5	1,31	74437069,61	993526,96	182253,95	120634336,44	19995049,81	215066455,86	1499663,33	295364,72	6658542,31	573708,73	37313958,55	27110898,55	1526472,17
6	1,38	74064884,26	941731,71	171888,80	120031164,76	19895074,56	213991123,58	1421481,83	278566,73	6311414,52	541080,75	35191837,69	25525673,36	27052145,52
7	1,45	73694559,84	892636,70	162113,13	119431008,94	19795599,19	212921167,96	1347376,14	262724,07	5982383,43	510308,38	33190406,16	24032864,31	51085009,84
8	1,53	73326087,04	846101,13	152893,43	118833853,89	19696621,19	211856562,12	1277133,79	247782,42	5670505,62	481286,10	31302800,12	22627097,64	73712107,48
9	1,62	72959456,60	801991,60	144198,06	118239684,62	19598138,09	210797279,31	1210553,35	233690,53	5374886,84	453914,38	29522546,09	21303311,33	95015418,80
10	1,71	72594659,32	760181,61	135997,23	117648486,20	19500147,40	209743292,92	1147443,94	220400,07	5094679,47	428099,35	27843538,73	20056737,07	115072155,87
11	1,80	72231686,02	720551,29	128262,79	117060243,77	19402646,66	208694576,45	1087624,58	207865,47	4829080,07	403752,46	26260019,94	18882883,28	133955039,15
12	1,90	71870527,59	682987,00	120968,22	116474942,55	19305633,43	207651103,57	1030923,78	196043,73	4577327,08	380790,24	24766559,09	17777519,04	151732558,19
13	2,01	71511174,95	647381,04	114088,51	115892567,84	19209105,26	206612848,05	977178,93	184894,33	4338698,65	359133,92	23358034,40	16736659,01	168469217,20
14	2,12	71153619,08	613631,32	107600,07	115313105,00	19113059,73	205579783,81	926235,96	174379,01	4112510,57	338709,24	22029615,38	15756549,21	184225766,41
15	2,23	70797850,98	581641,06	101480,63	114736539,47	19017494,44	204551884,89	877948,77	164461,72	3898114,28	319446,16	20776746,26	14833653,63	199059420,04
16	2,36	70443861,73	551318,54	95709,22	114162856,77	18922406,96	203529125,47	832178,93	155108,45	3694895,06	301278,61	19595130,36	13964641,55	213024061,59
17	2,48	70091642,42	522576,82	90266,04	113592042,49	18827794,93	202511479,84	788795,20	146287,11	3502270,20	284144,28	18480715,36	13146375,72	226170437,31
18	2,62	69741184,21	495333,48	85132,43	113024082,28	18733655,95	201498922,44	747673,17	137967,47	3319687,39	267984,41	17429679,42	12375901,07	238546338,38
19	2,77	69392478,29	469510,40	80290,77	112458961,87	18639987,67	200491427,83	708694,95	130120,98	3146623,12	252743,59	16438418,03	11650434,21	250196772,59
20	2,92	69045515,90	445033,56	75724,47	111896667,06	18546787,74	199488970,69	671748,77	122720,73	2982581,15	238369,55	15503531,70	10967353,46	261164126,05
21	3,08	68700288,32	421832,76	71417,87	111337183,72	18454053,80	198491525,84	636728,69	115741,35	2827091,14	224812,99	14621814,25	10324189,45	271488315,51
22	3,25	68356786,88	399841,48	67356,19	110780497,80	18361783,53	197499068,21	603534,30	109158,91	2679707,24	212027,42	13790241,88	9718616,35	281206931,85
23	3,43	68015002,94	378996,66	63525,51	110226595,31	18269974,61	196511572,87	572070,43	102950,82	2540006,87	199968,98	13005962,72	9148443,46	290355375,31
24	3,61	67674927,93	359238,54	59912,68	109675462,34	18178624,74	195529015,00	542246,85	97095,79	2407589,45	188596,34	12266287,12	8611607,46	298966982,77
25	3,81	67336553,29	340510,46	56505,32	109127085,03	18087731,61	194551369,93	513978,06	91573,76	2282075,30	177870,48	11568678,37	8106164,98	**307073147,75**
	53,97	1788947495,92	17417991,55	3113332,47	2899207279,91	480541408,77	5168696184,60	26291308,01	5045534,42	116734058,19	9800314,50	637411475,37		
										24,90				
										0,29				

Annex III: Calculation of the different LCOEs for the three power plant based on CSP, biomass combustion and hybrid CSP-biomass technologies

The following is a particular of the excell sheet utilized for the calculation of the LCOEs of the three power plants based on the different technologies under study, in the case of a total installed capacity of 25 MW and 50 MW. The cost of the biomass feedstock is assumed to be 70€/tonne. The same calculations are performed in the different cases of the feasibility study, for different prices of the biomass feedstock, with consequent different O&M costs, or locations, with consequent higher or lower electricity generations.

Solar 25 MW		
WACC	5,50%	10%
n	25	25
CAPEX	114917247	114917247
OPEX	777066,30	645963,22
alfa	0,07454935	0,11016807
beta	0,01954935	0,01016807
net Gen	34175,07	34175,07
Decomm	459668,987	11491724,7
LCOE	273,680725	392,772334

Biomass 25 MW		
WACC	5,50%	10%
n	25	25
CAPEX	41677013,6	41677013,6
OPEX	4476860,92	4476860,92
alfa	0,07454935	0,11016807
beta	0,01954935	0,01016807
net Gen	100200,00	100200,00
Decomm	166708,054	166708,054
LCOE	75,7197041	90,519284

Hybrid 25 MW		
WACC	5,50%	10%
n	25	25
CAPEX	151935789	151935789
OPEX	3568050,78	3746695,63
alfa	0,07454935	0,11016807
beta	0,01954935	0,01016807
net Gen	98739,94	98739,94
Decomm	607743,154	607743,154
LCOE	150,968758	207,528459

Solar 50 MW		
WACC	5,50%	10%
n	25	25
CAPEX	201105182	206851044
OPEX	1269757,24	1269757,24
alfa	0,07454935	0,11016807
beta	0,01954935	0,01016807
net Gen	68350,15	68350,15
Decomm	804420,727	20110518,2
LCOE	238,152294	354,975434

Biomass 50 MW		
WACC	5,50%	10%
n	25	25
CAPEX	72934773,8	75018624,5
OPEX	8524475,99	8524475,99
alfa	0,07454935	0,11016807
beta	0,01954935	0,01016807
net Gen	200400,00	200400,00
Decomm	291739,095	291739,095
LCOE	69,6977021	83,7929124

Hybrid 50 MW		
WACC	5,50%	10%
n	25	25
CAPEX	265887630	273484419
OPEX	7136101,57	6993856,41
alfa	0,07454935	0,11016807
beta	0,01954935	0,01016807
net Gen	197479,885	197479,885
Decomm	1063550,52	607743,154
LCOE	136,614644	188,01554